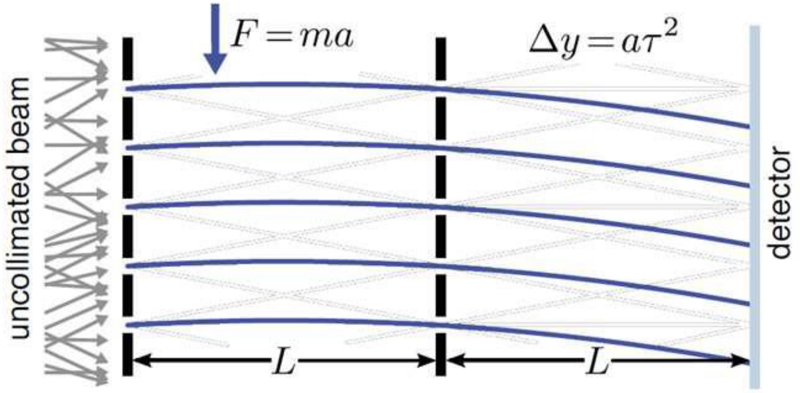
The AMPIS project

Status and Outlook

R. Caravita
INFN - TIFPA

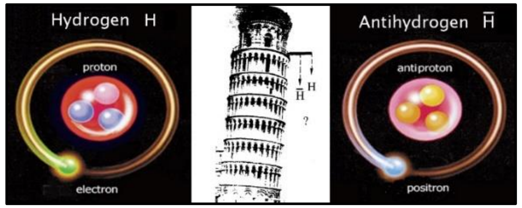
H2020 MSCA COFUND G.A. 754496

Testing the universality of the free fall with cold antiatoms

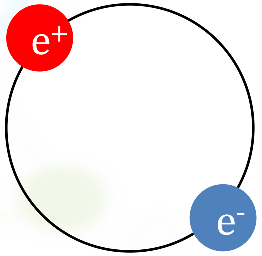


One needs

- an intense beam of cold antiatoms ⟵ the **real** bottleneck
- a very high-resolution imaging detector for antiparticles
- a classical deflectometer/light interferometer



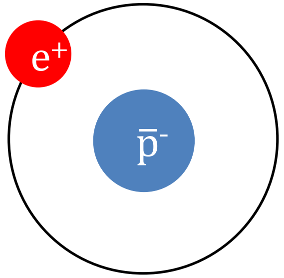
AMPIS



Positronium (Ps)

- electron + positron
- short-lived (only 142 ns!)
- table-top experiments

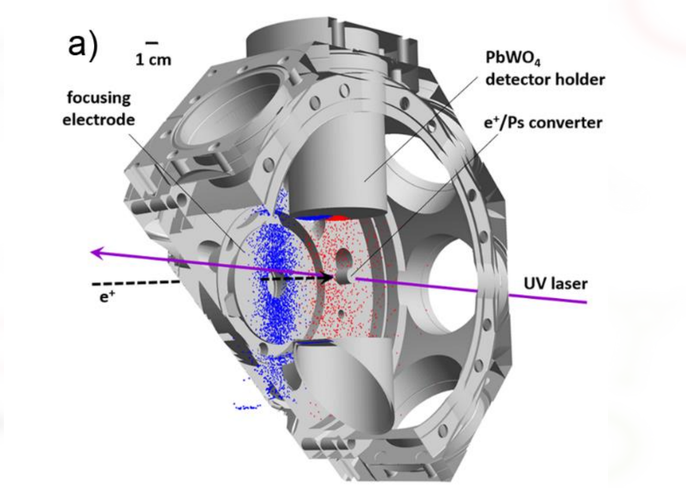
AEgIS

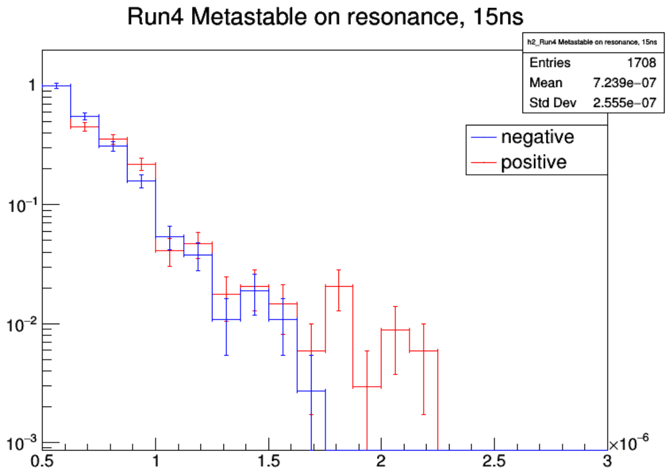


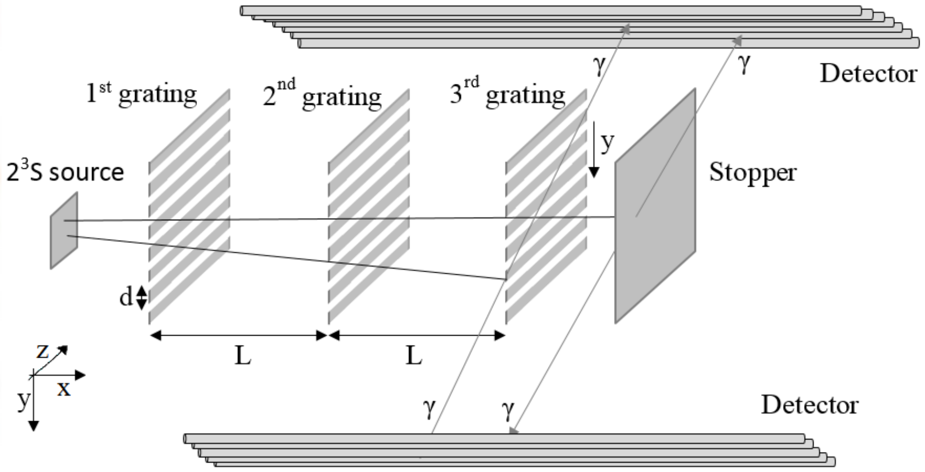
Antihydrogen ($\bar{H}$)

- antiproton + positron
- only «stable» atom
- small amounts only @ CERN

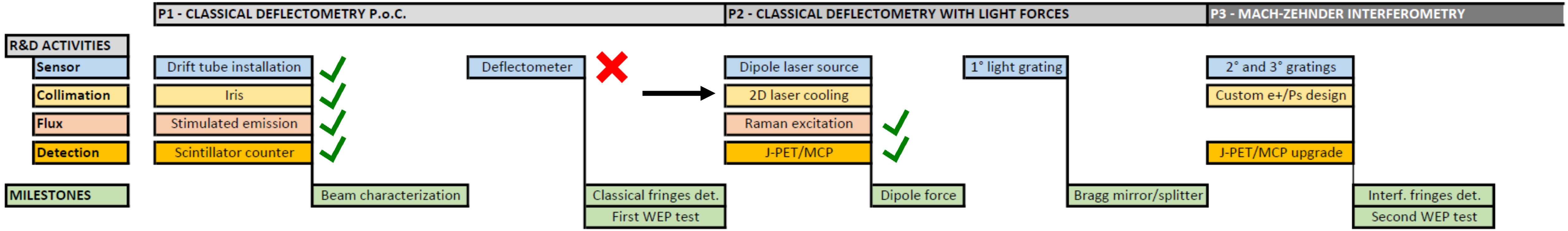
Two joint ventures with one single goal – developing the first source of cold antiatoms for a test of the Universality of the Free-Fall







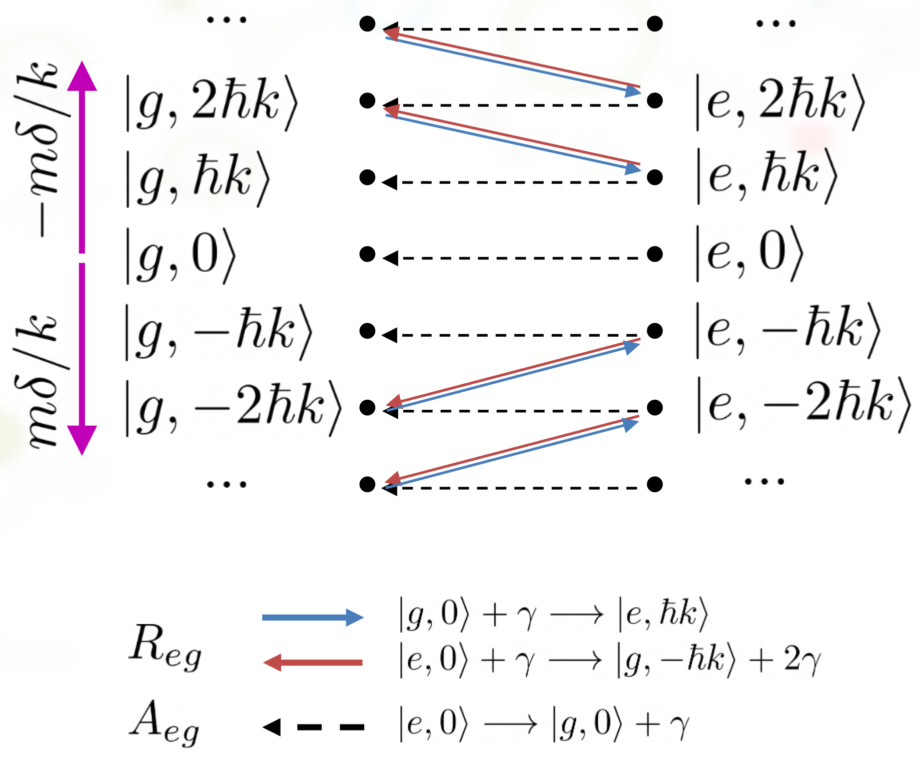
Submitted StG

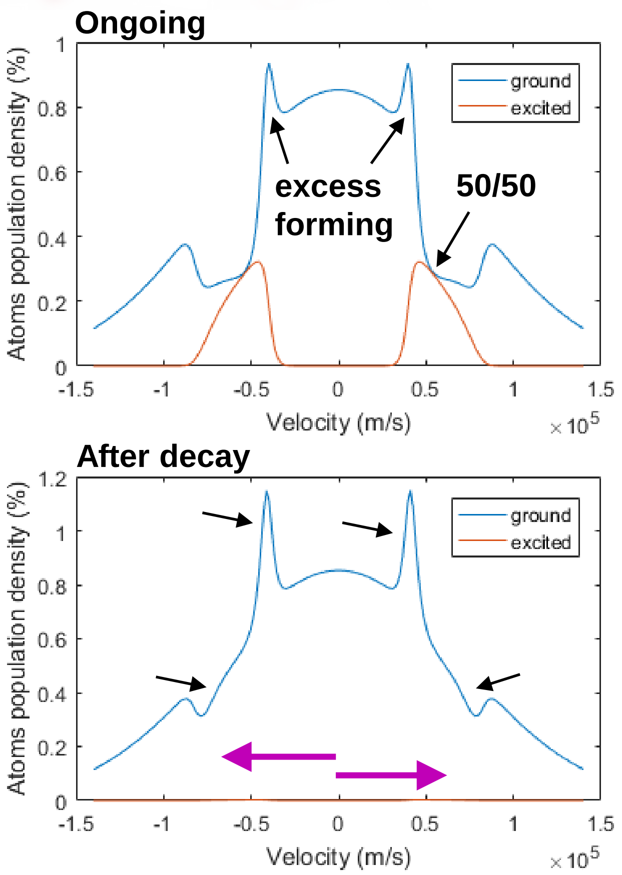


The crucial step: a laser cooled beam of Ps to enhance its collimation

A word about laser cooling in general

Consider now an extra counter-propagating laser with negative photon momenta i.e., symmetric w.r.t. null velocity along its propagation axis. Transitions with negative momentum exchange are now allowed, leading to a symmetrical effect on the velocity distribution as the sign of the velocity detuning $m\delta/k$ is also inverted by the $k \rightarrow -k$ transformation.





Secondment, 2021

Laser cooling positronium

PHYSICAL REVIEW A VOLUME 48, NUMBER 1 JULY 1993

Measurement of the positronium $1\,^3S_1-2\,^3S_1$ interval by continuous-wave two-photon excitation

M. S. Fee* and S. Chu
Physics Department, Stanford University, Stanford, California 94305

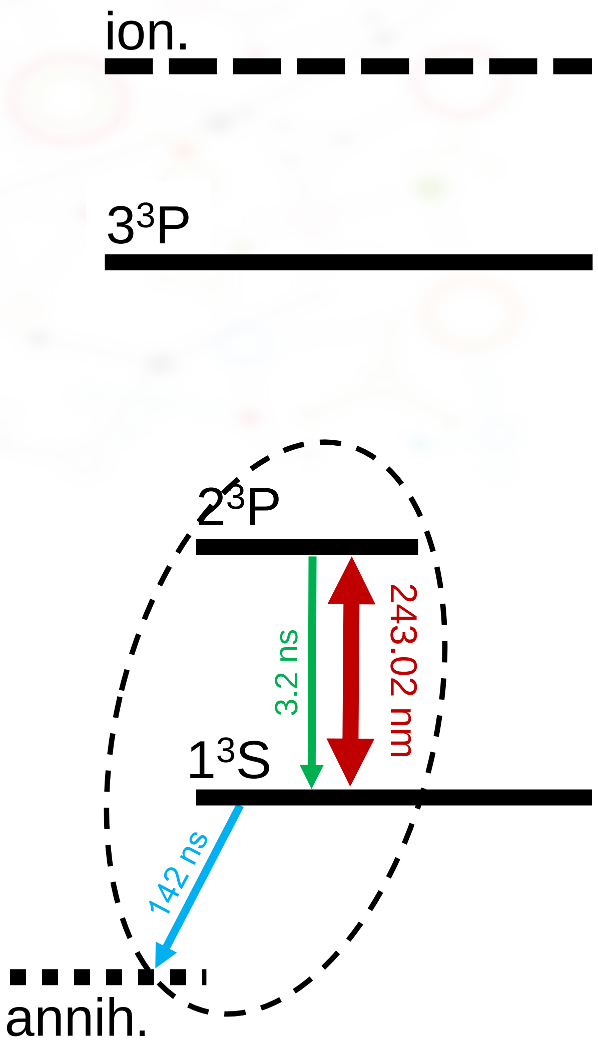
A. P. Mills, Jr., R. J. Chichester, and D. M. Zuckerman
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

The ultimate reduction in the positronium temperature would, of course, be achieved by laser cooling the atoms. Subkelvin positronium temperatures may be possible with laser cooling techniques. The laser cooling of positronium presents an unusual challenge since (i) the ground-state atom annihilates in 140 ns, (ii) the Doppler width at room temperature is ~500 GHz, and (iii) the single photon recoil velocity corresponds to a Doppler shift of 6.1 GHz. Thus, the "chirped slowing" commonly used for heavier atoms is not feasible. Even if it were possible to

Strong impact on the community

- Cold beam for interferometric studies
- Higher resolution spectroscopy – limited by T
- Opens to the possibility of antimatter BECs
- Achievement awaited for 30 years!

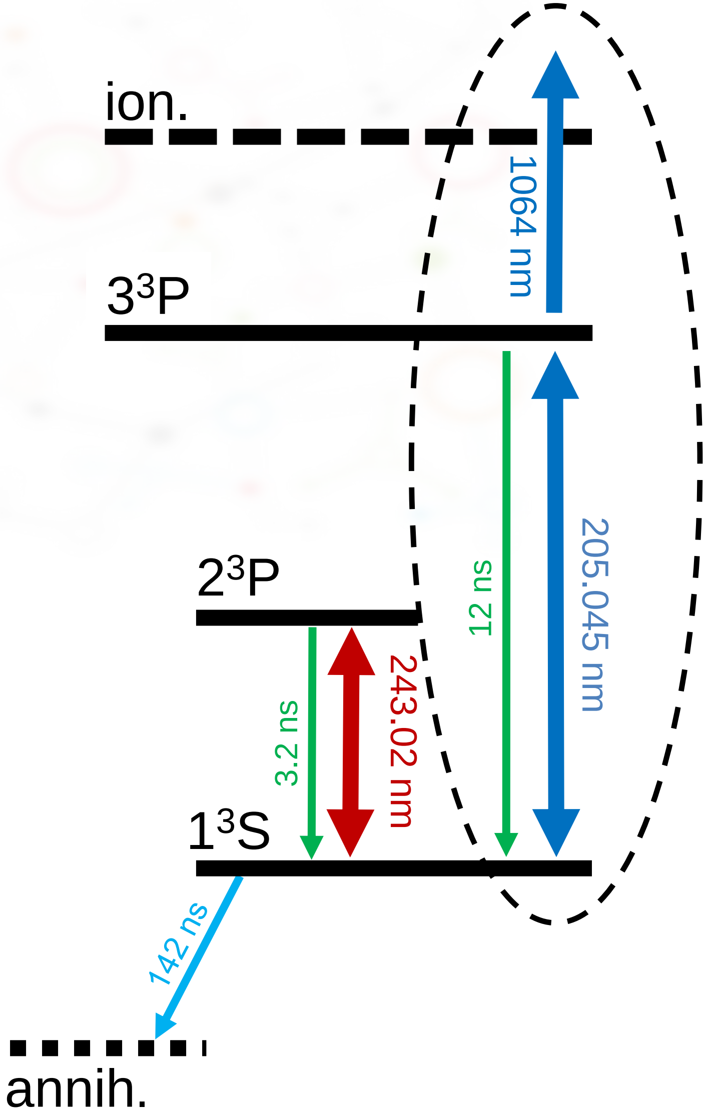
- **Cooling transition**
  - $1^3S \rightarrow 2^3P$
  - Wavelength = 243.024nm
  - Lifetime = 3.2ns



Effective two-level system with an extra loss mechanism (annihilation from the ground state)

- **Cooling transition**
  - $1^3S \rightarrow 2^3P$
  - Wavelength = 243.024nm
  - Lifetime = 3.1ns
- **Probing transition**
  - Intermediate state excitation
    - $1^3S \rightarrow 3^3P$
    - Wavelength = 205.045nm
  - Photoionization
    - $3^3P \rightarrow$ continuum
    - Wavelength = 1064nm

Two-step incoherent photoionization sensitive to the Ps velocity distribution through the probe laser bandwidth



Laser cooling positronium

- **Cooling transition**
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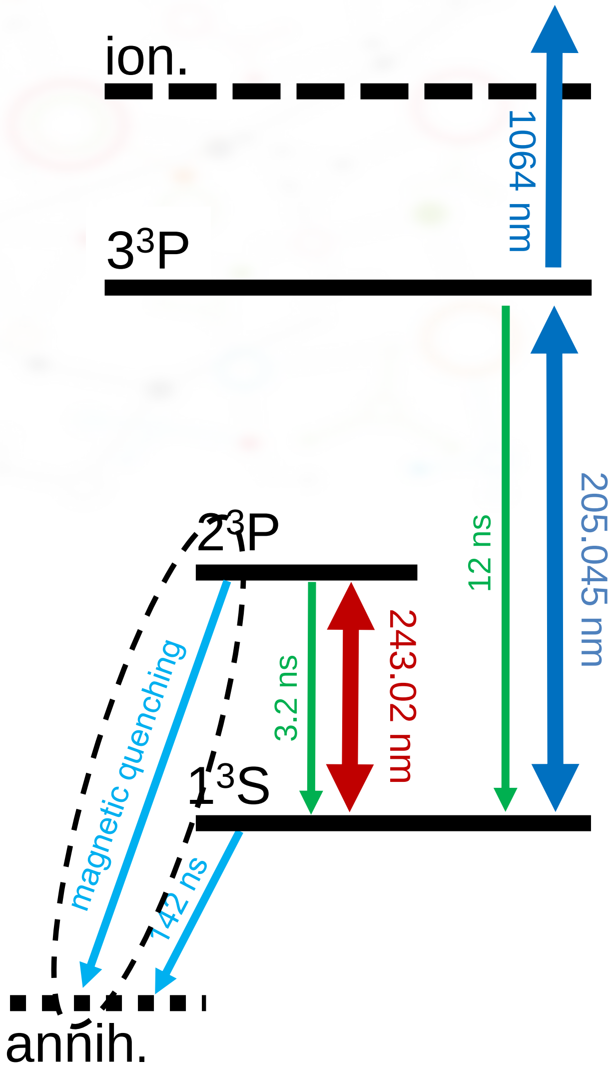
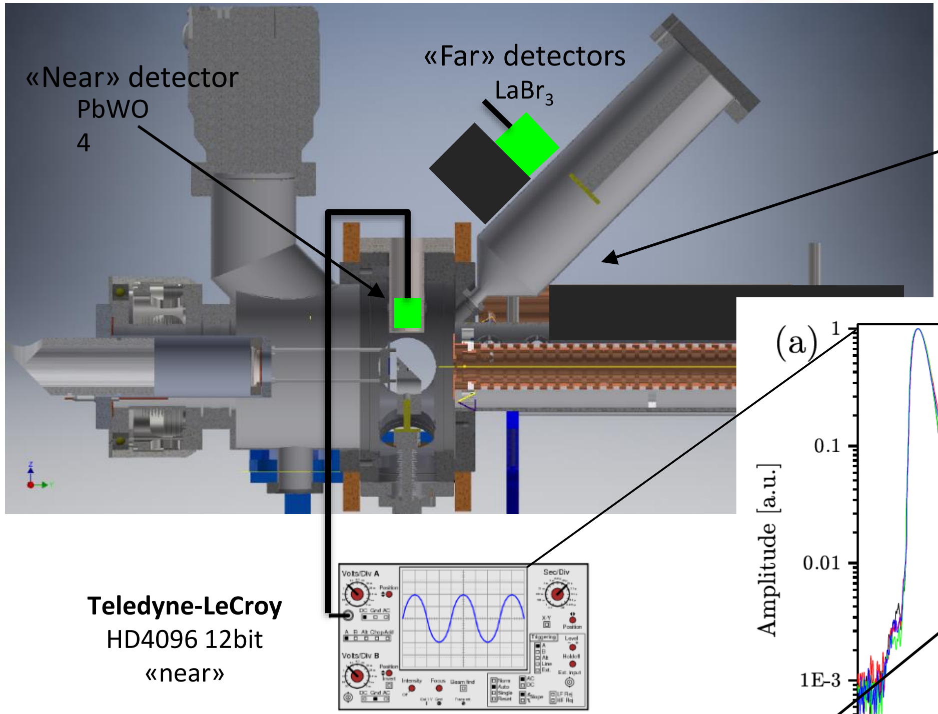


Magnetic quenching is our primary competing effect altering natural spontaneous emission cycles

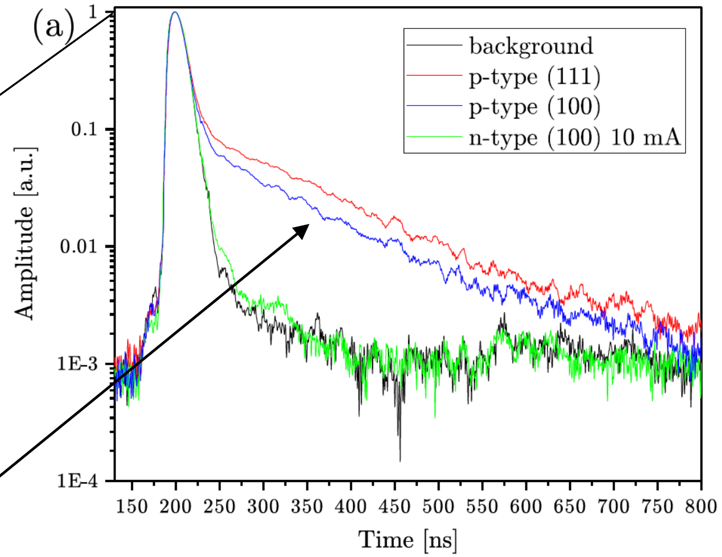
Single-Shot Positron Annihilation Lifetime Spectroscopy (SSPALS)



150 G transport magnetic field

Teledyne-LeCroy
HD4096 12bit
«near»

PbWO$_4$ SSPALS spectrum

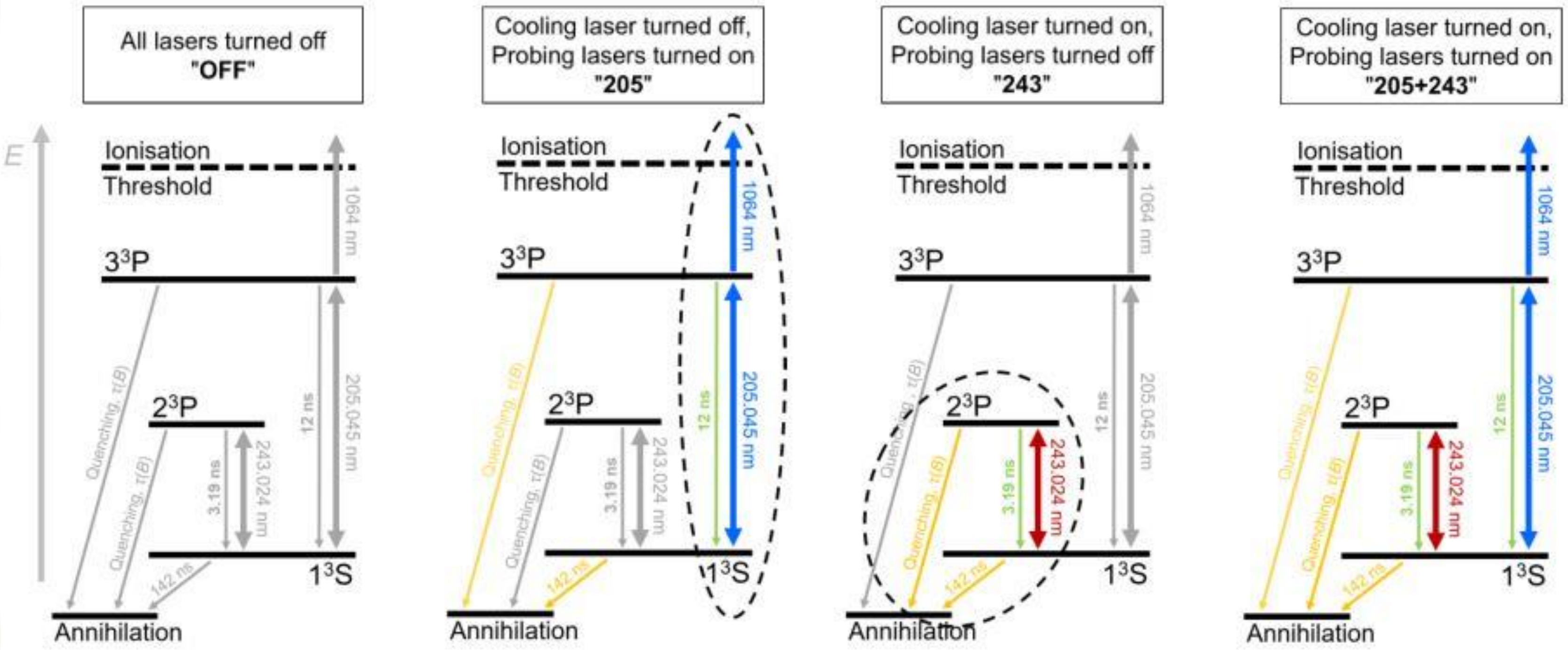


Observable proportional to the emitted 1^3S Ps

$$A_X := \int_{250\ \mathrm{ns}}^{550\ \mathrm{ns}} V_X(t)dt$$

X denotes a certain measurement class (see next slide)

Measurement classes in a laser cooling run



A_{off}

Amount of 1³S Ps in ground state

A_{205}

Amount of 1³S Ps surviving photoionization by probe laser

A_{243}

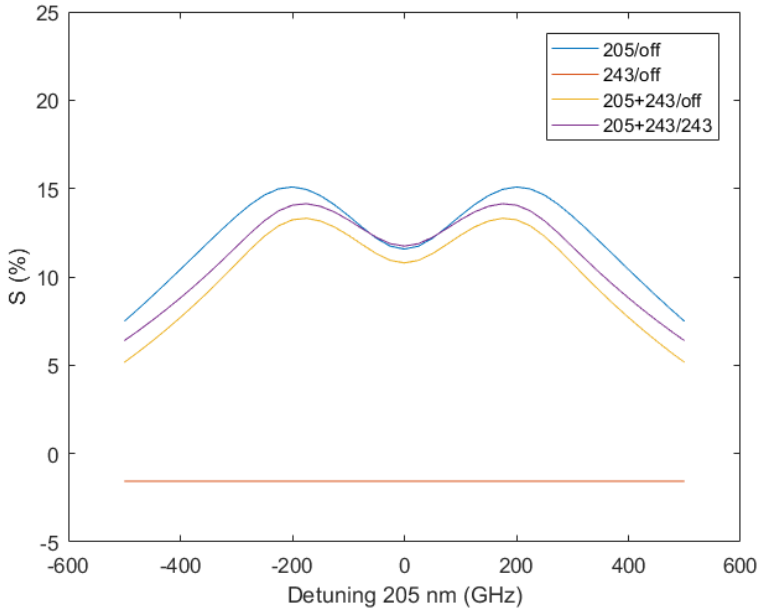
Amount of 1³S Ps surviving quenching and cooling cycles

$A_{205+243}$

Amount of 1³S Ps surviving quenching, cooling cycles and subsequent photoionization

In a typical SSPALS experiment, one constructs the S parameters by comparing the 1^3S Ps amount in a background reference measurement (**bck**) to the amount in the signal measurement (**sig**)

$$S^{\mathrm{sig}}_{\mathrm{bck}} := \frac{A_{\mathrm{sig}} - A_{\mathrm{bck}}}{A_{\mathrm{bck}}}$$



Oservable for laser cooling:

$$S^{205+243}_{243} := \frac{A_{205+243} - A_{243}}{A_{243}}$$

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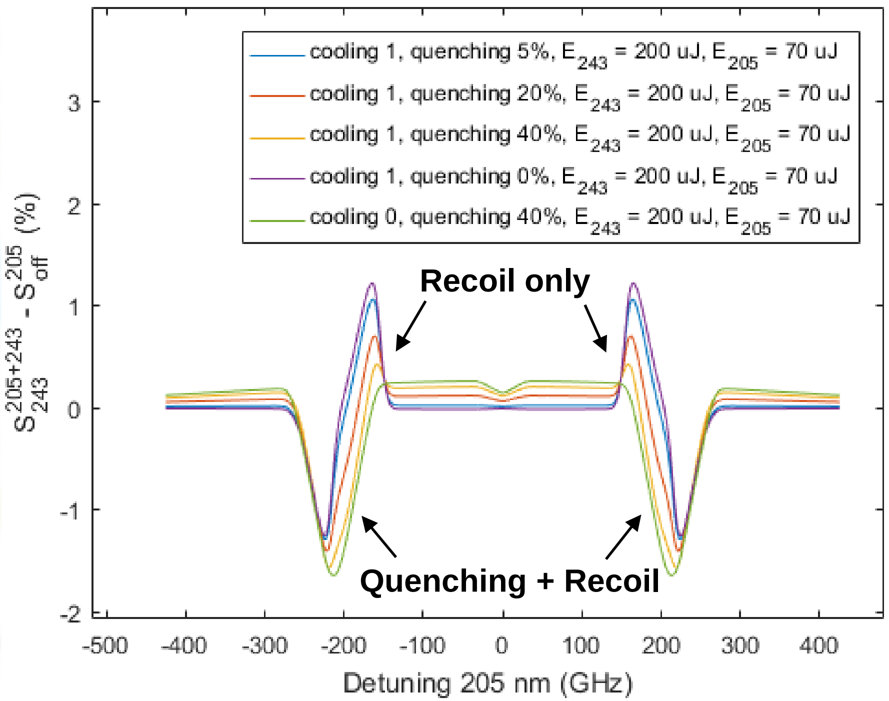
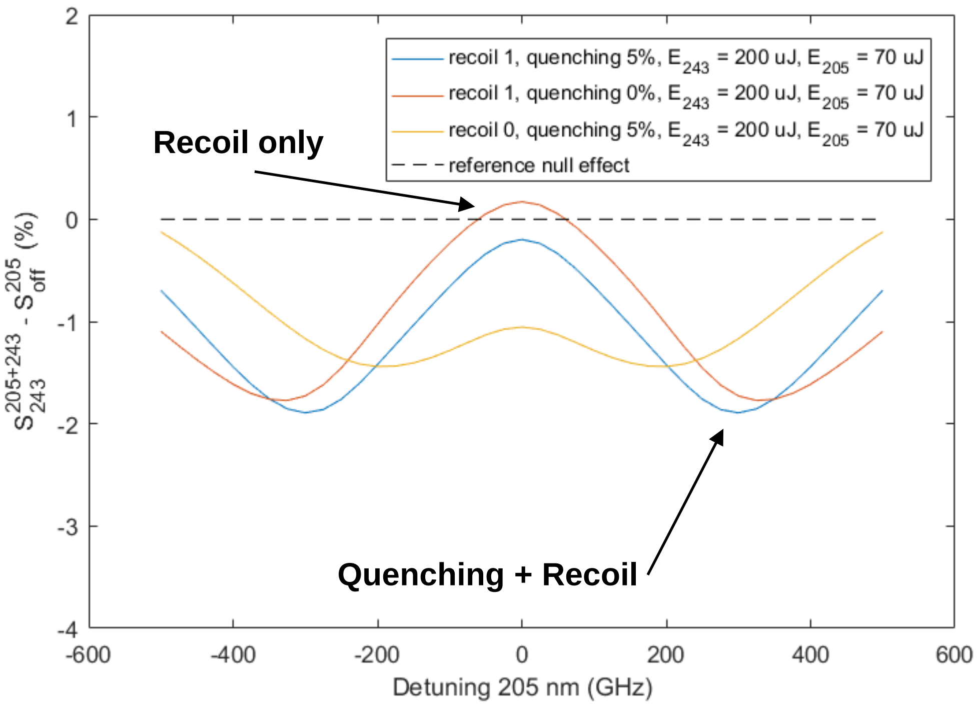
Expected signal

$$S_{243}^{205+243} := \frac{A_{205+243} - A_{243}}{A_{243}}$$





Exaggerated case

$\sigma_{243} = 5.5$ GHz $\sigma_{205} = 11$ GHz

$E_{243} = 200\ \mu J$ and $E_{205} = 70\ \mu J$

Realistic case

$\sigma_{243} = 55$ GHz $\sigma_{205} = 110$ GHz

$E_{243} = 200\ \mu J$ and $E_{205} = 70\ \mu J$

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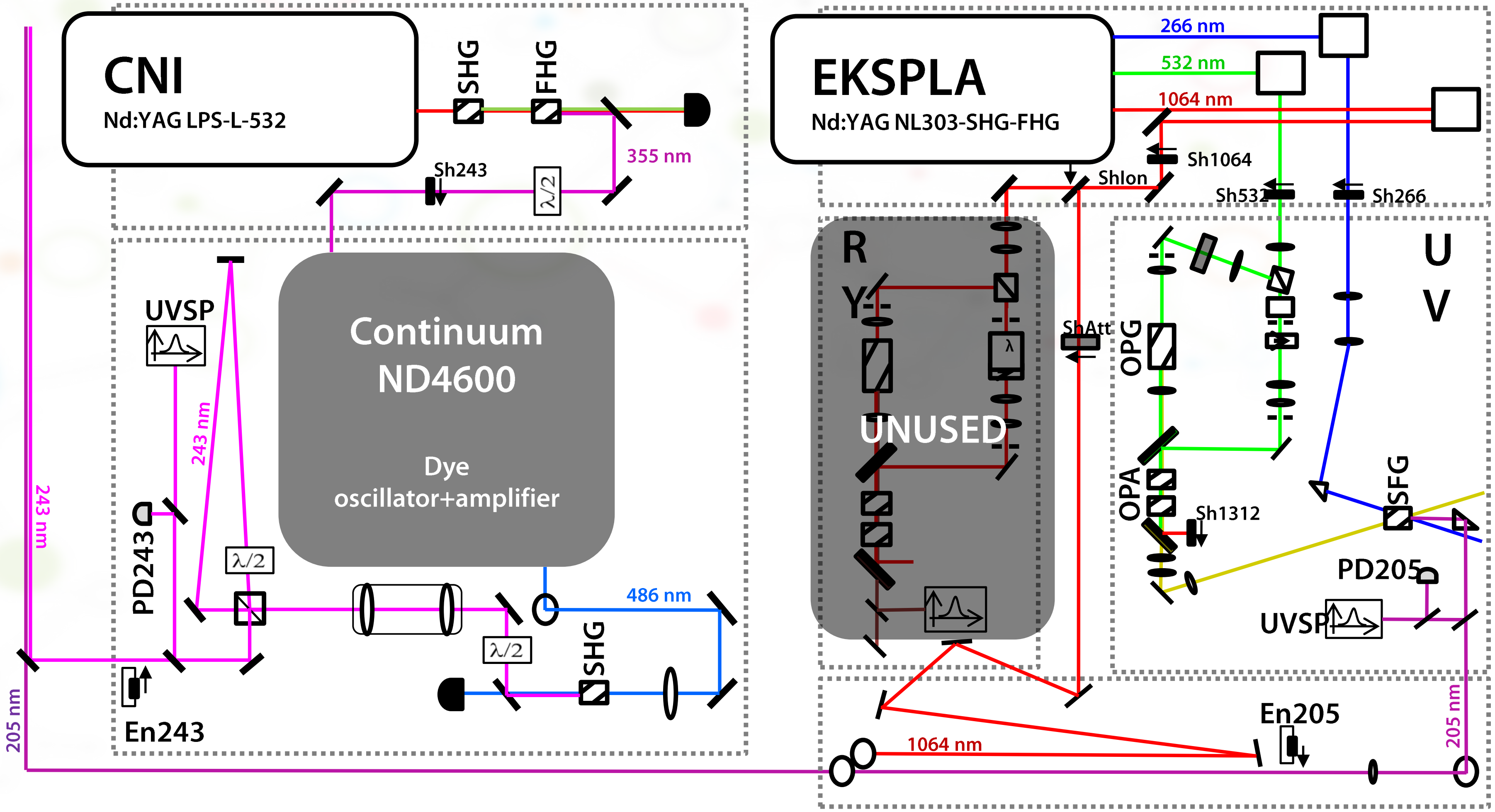
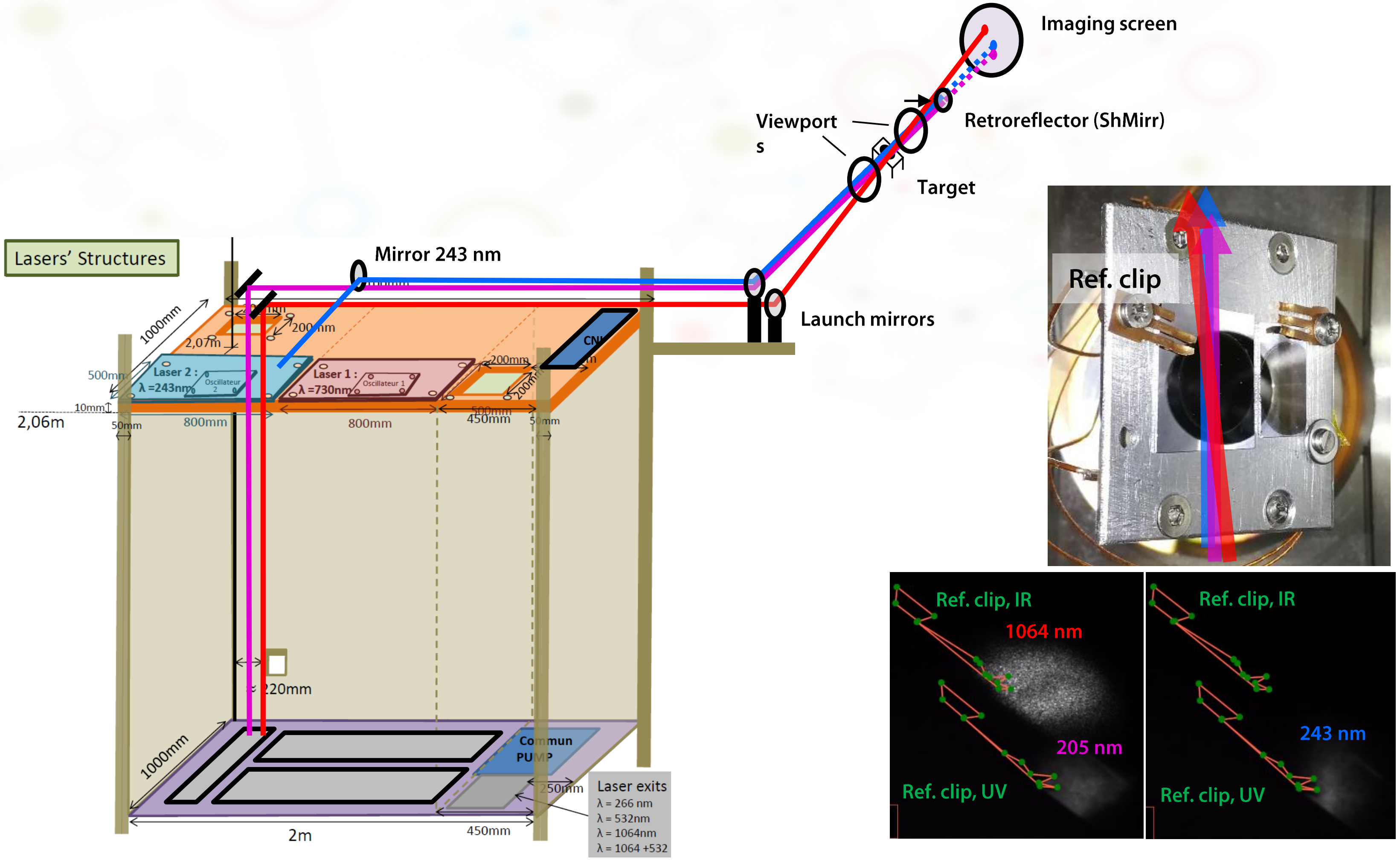
The two lasers used in the first study

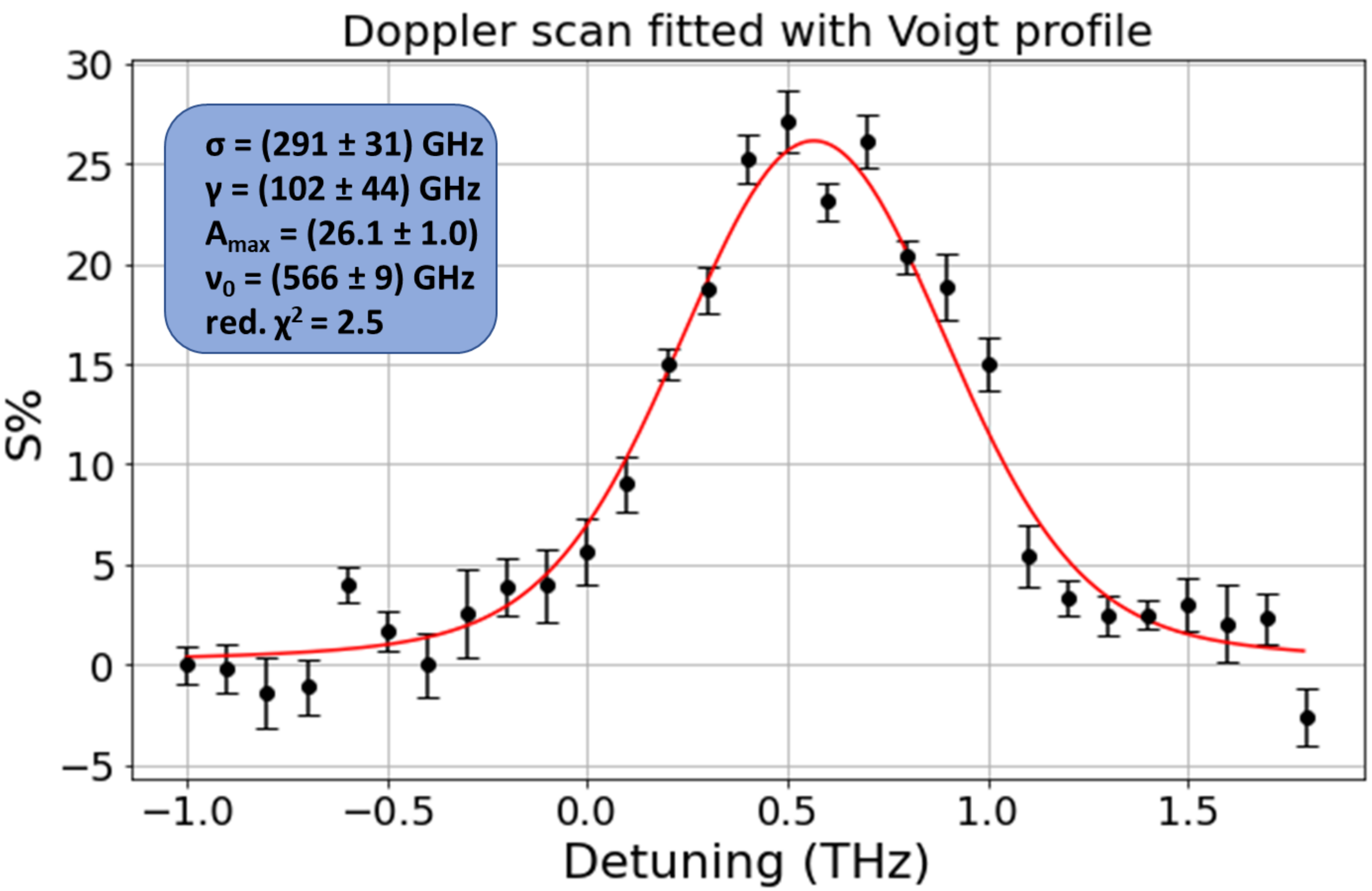


Supervision of one PhD student (CZ)

Overall experimental setup

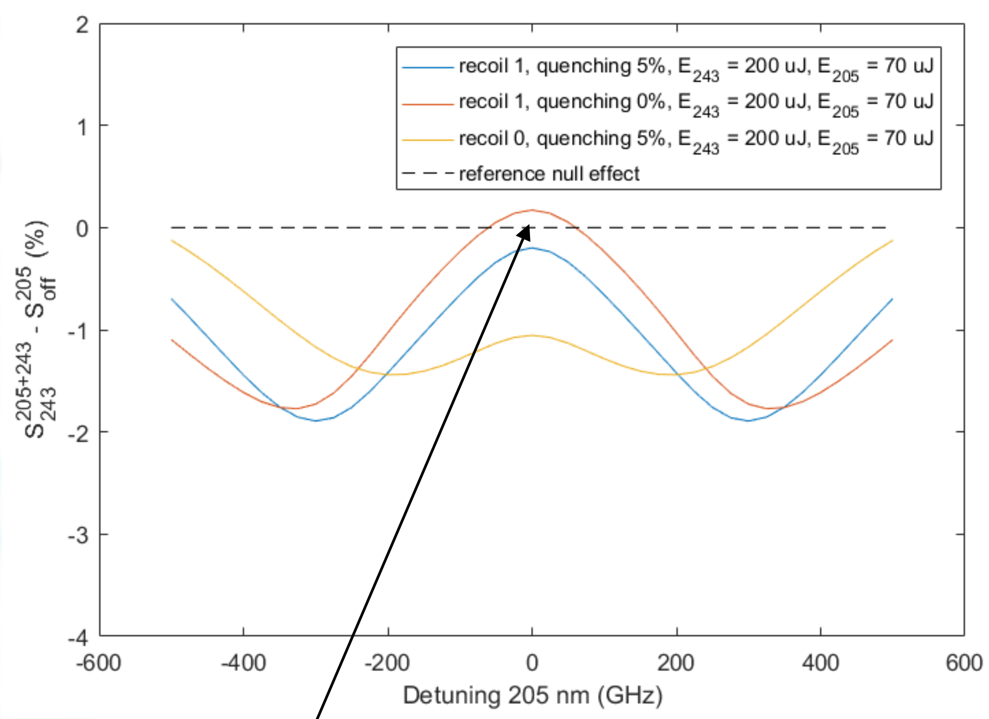


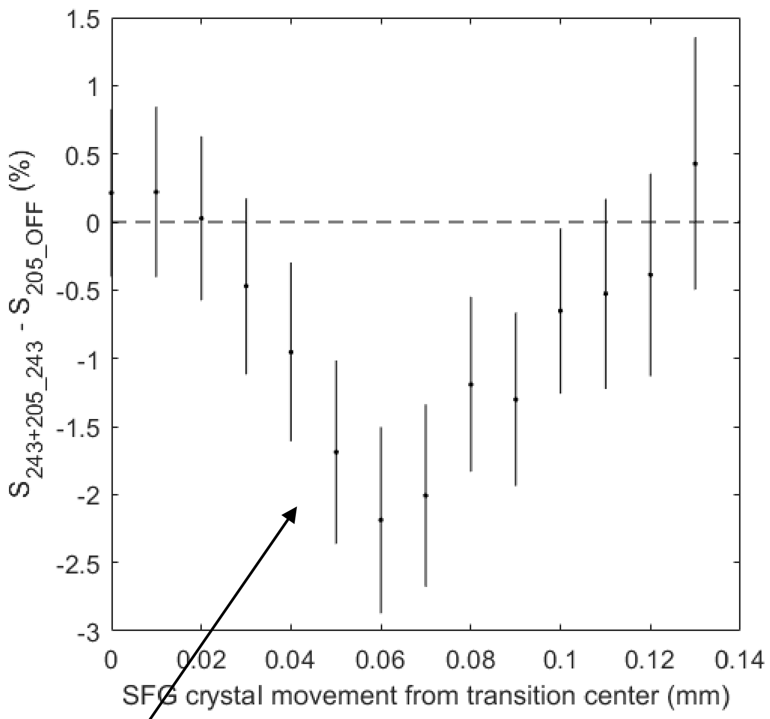
The probed 1S-3P transition line



Best 1S-3P transition measurement so far

Comparison with expected signal





Negative peak amplitude consistent with ~5% quenching

We must reduce quenching to as close to 0% as possible to observe an excess

Get rid of the 150 G magnetic field, and try again with higher statistics (~ one integrated month of data taking with the single $PbWO_4$)

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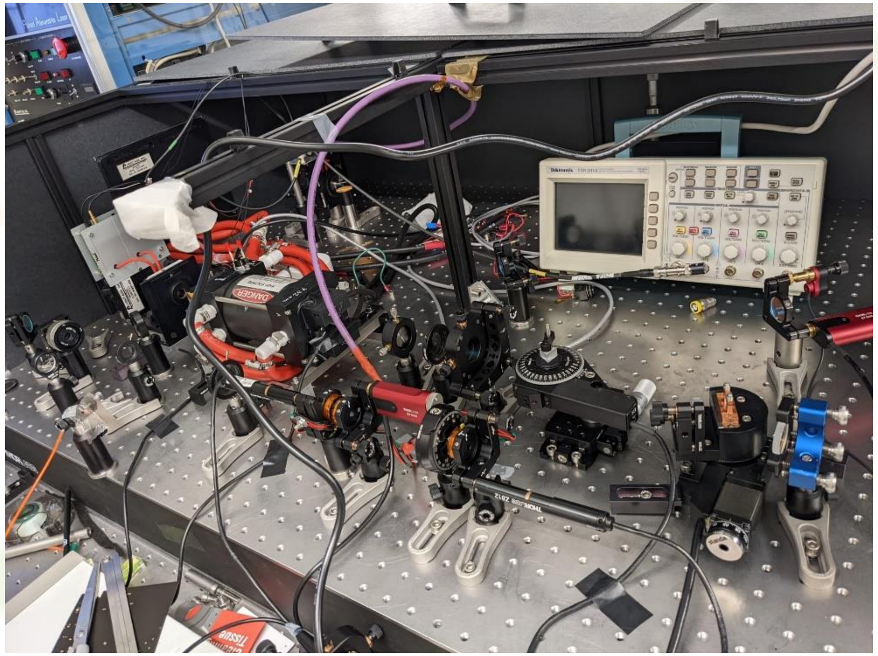
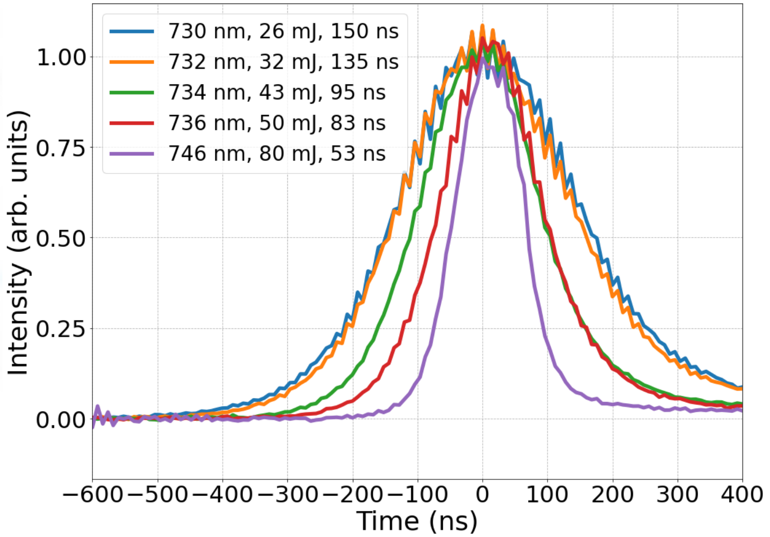
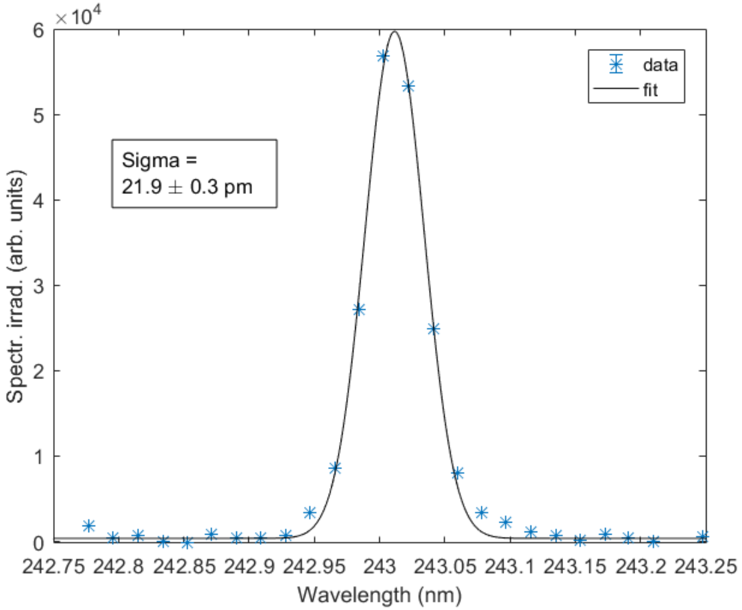
Improved cooling laser

Supervision of one PhD student (NG)







Tripled Alexandrite laser
Broadband long pulses at 243 nm
(an idea I’ve been proudly pushing for years ☺)

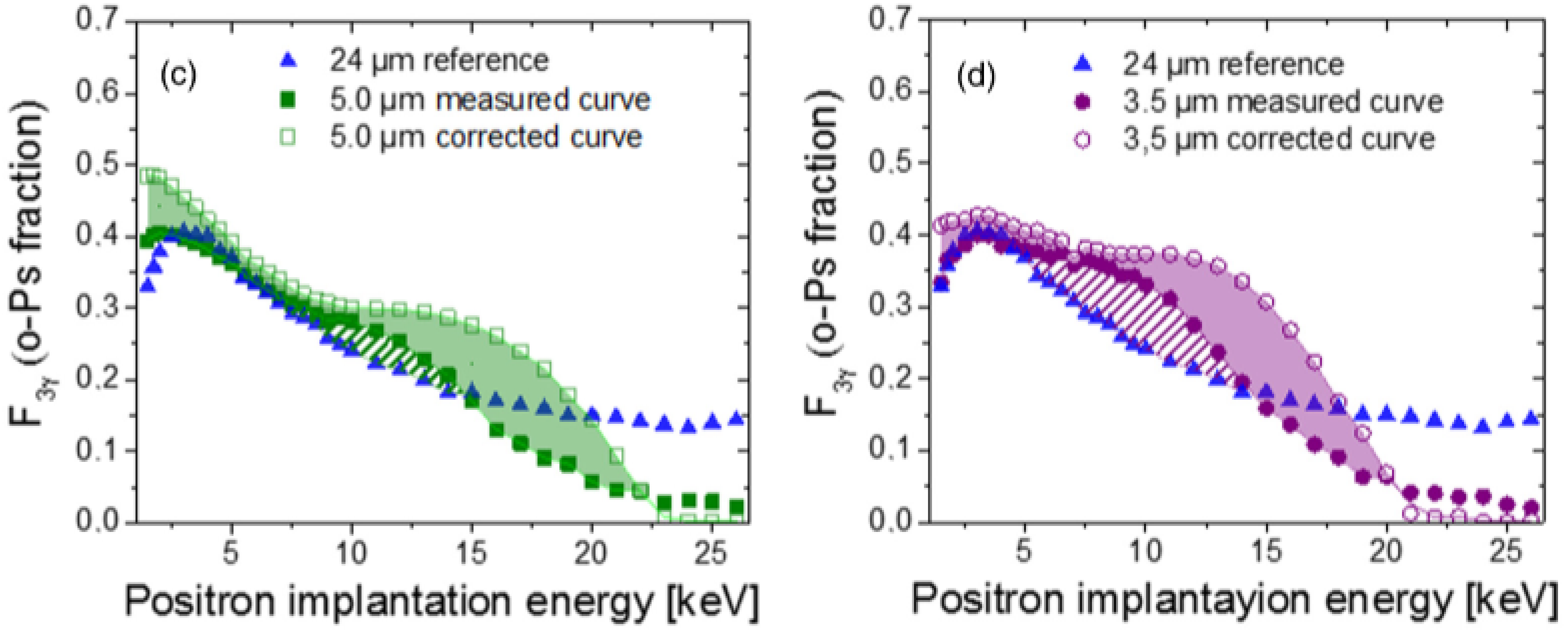
FELLINI support for line broadening with RF generator

The future – transmission Ps geometries

PHYSICAL REVIEW B **105**, 115422 (2022)

Forward emission of positronium from nanochanneled silicon membranes

S. Mariazzi,[1,2,*] B. Rienäcker,[3,†] R. Magrin Maffei,[4,5] L. Povolo,[1,2] S. Sharma,[2] R. Caravita,[2] L. Penasa,[1,2]
P. Bettotti,[1] M. Doser,[3] and R. S. Brusa[1,2]



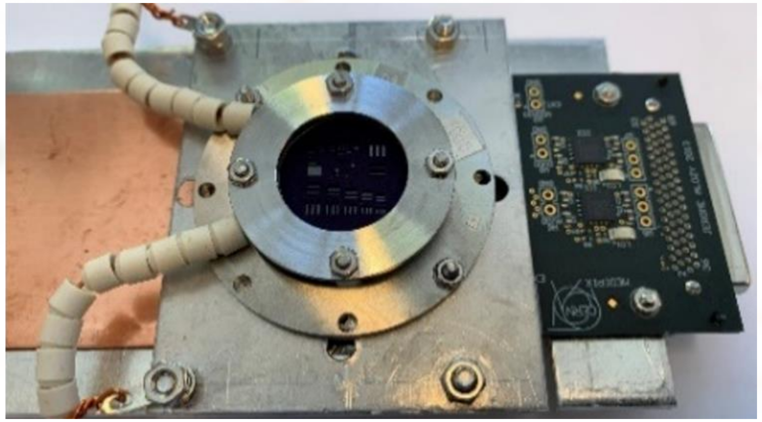
Published with FELLINI acknowledgment

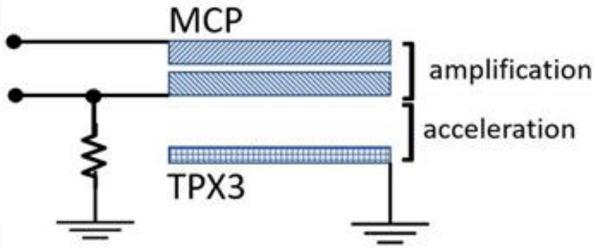
Improved Position- and timing- sensitive detector

Supervision of one PhD student (LG)

MCP-TimePix3 ASIC hybrid

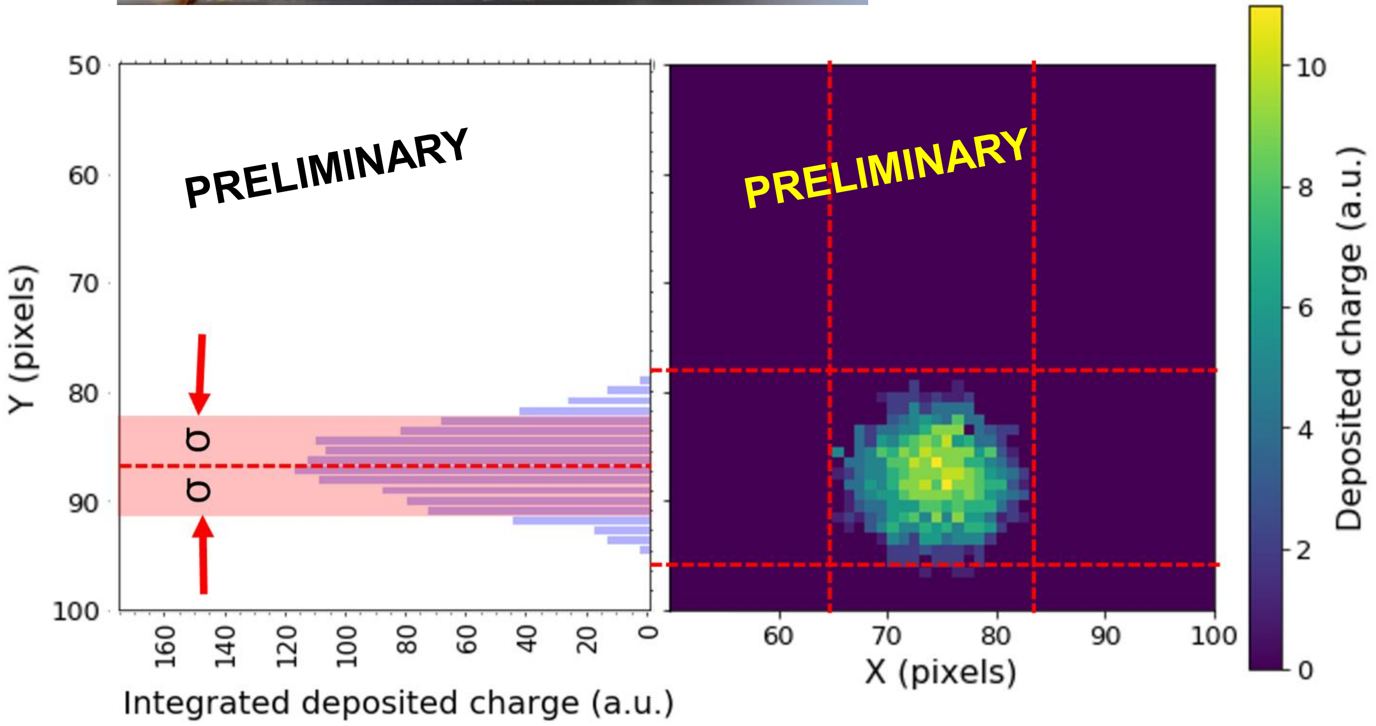
- Event-by-event reconstruction with positional and timing informations
- 10 bit charge readout of TimePix3: 2D centroiding reconstruction and sub-pixel resolution
- Benefits from the high detection efficiency of chevron MCPs





Preliminary results (with e^+)

- 15 ns timing resolution
- 12 um spatial resolution
- 41 % total detection efficiency

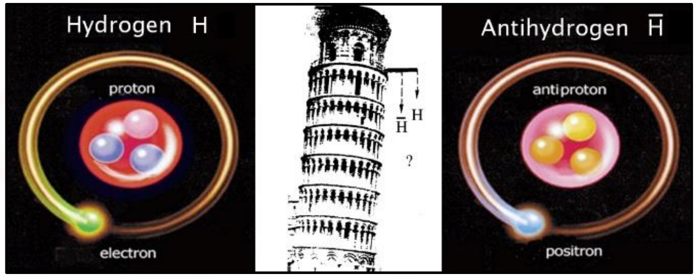


Resolution down to 5 um with UV light

In press (with FELLINI ack.)

Conclusions

- Many technological **advances** towards the **first beam of cold, long-lived positronium** atoms for inertial measurements
- Development of efficient positron-positronium targets suitable for **transmission** geometries
- Development of a novel **detector** for **high-resolution** timing and imaging antimatter events
- Solid perspective to establish soon **laser cooling of positronium**
- Constructing the first inertial sensor employing antimatter atoms is within reach!



Thank you for your attention

INFN
Istituto Nazionale di Fisica Nucleare

CERN

Fellini
Fellowship for Innovation at INFN

H2020 MSCA COFUND G.A. 754496

The AEgIS collaboration

The Antimatter Experiment: Gravity, Interferometry, Spectroscopy (**AEgIS**) collaboration aims at performing direct experimental tests of the Weak Equivalence Principle (**WEP**) using **anti-atoms**.

The chosen method is the **direct detection of the free-fall trajectory** of antihydrogen atoms, produced in a **pulsed** fashion

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Lyon 1
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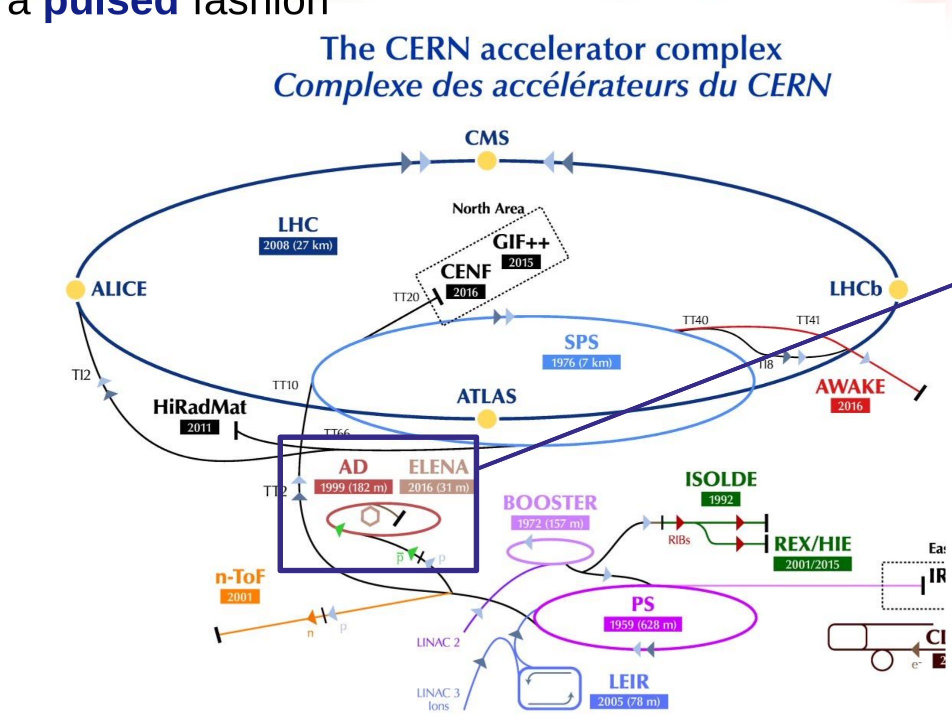
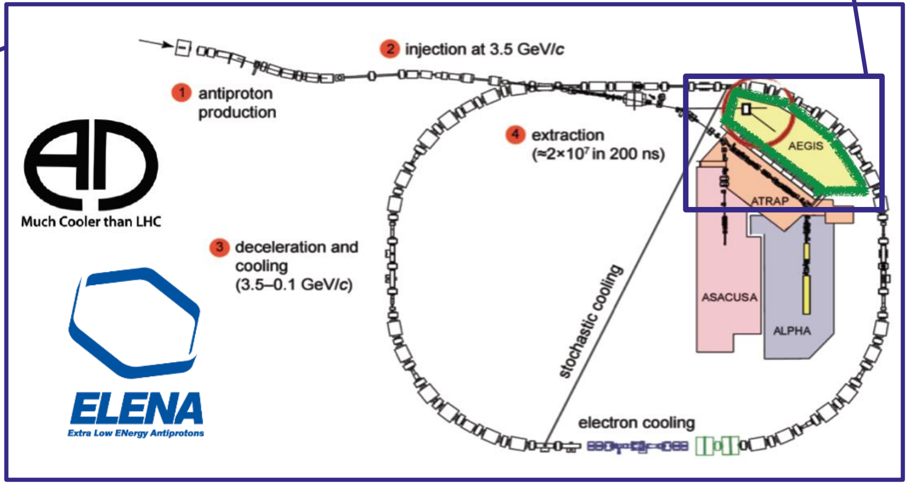
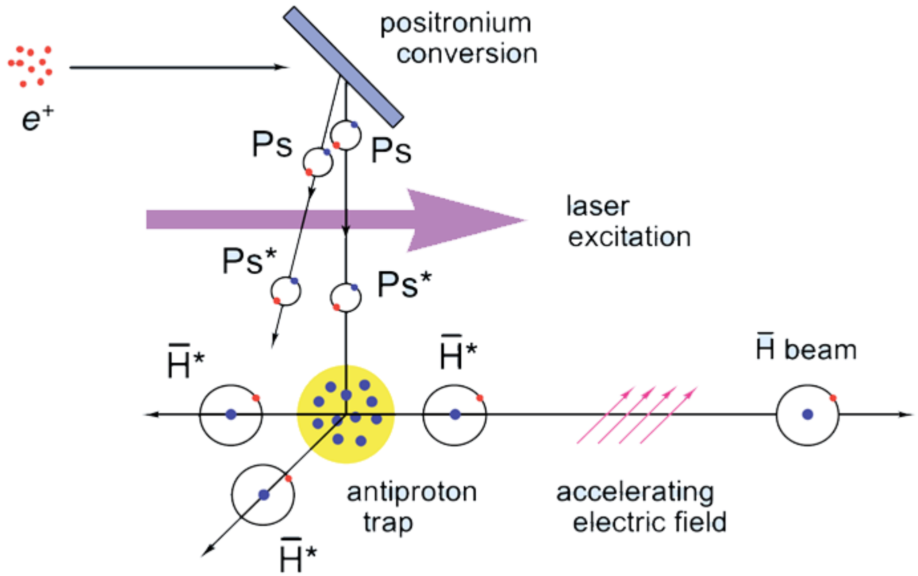
RRI





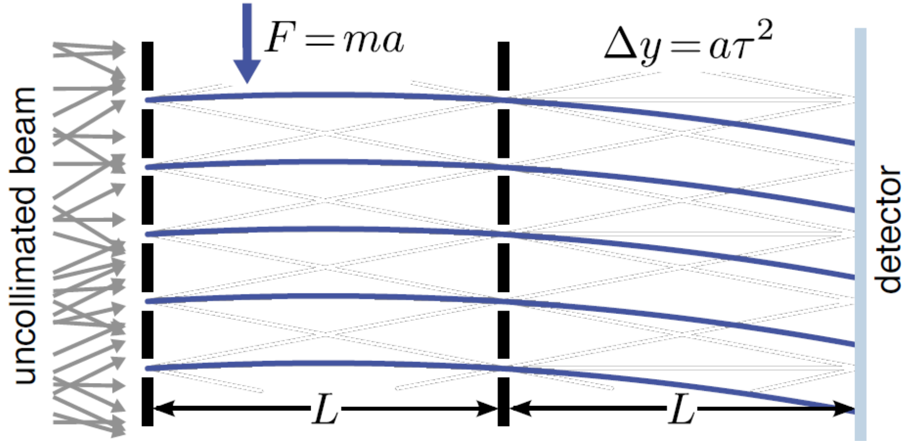


Pulsed antihydrogen source

1) Cold antiproton ($\bar{p}$) plasma preparation in a Penning trap
2) Pulsed positronium (Ps) from positron (e^+) conversion
3) Two-step laser excitation of Ps to Rydberg levels (Ps*)
4) Rydberg antihydrogen ($\bar{H}^*$) via charge-exchange, $\sigma \propto n_{Ps}^4$
5) Beam formation

Inertial sensing with a moiré deflectometer

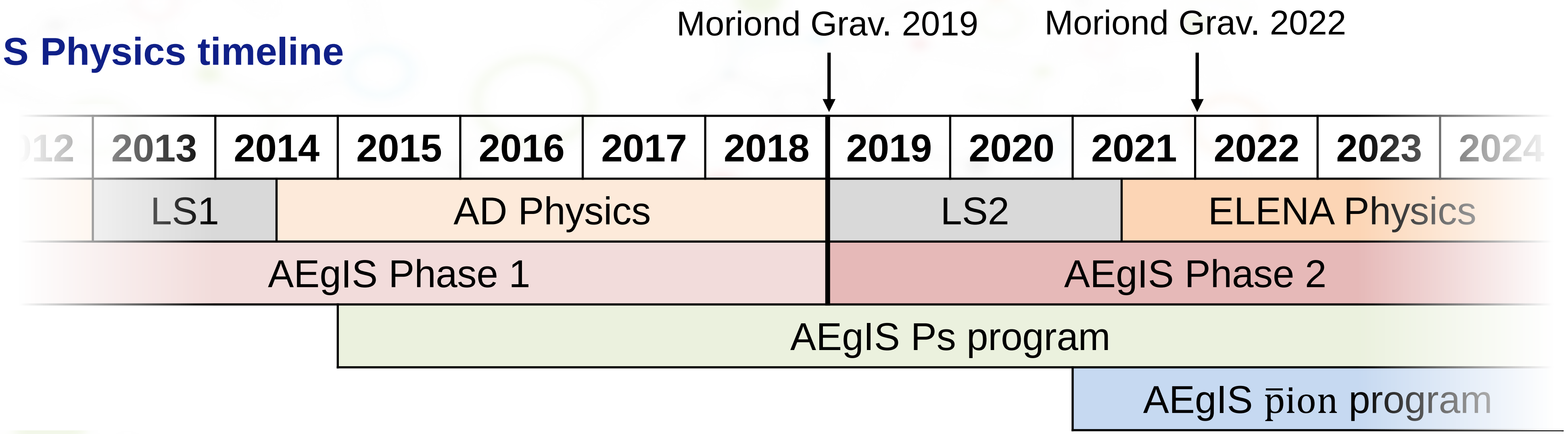
1) Anti-atoms from an incoherent, uncollimated source
2) A set of two gratings selects the trajectories
3) Probed by a position- and timing-sensitive detector



AEgIS experiment status

AEgIS concluded its **Phase 1** in 2018, achieving its goal of demonstrating the first pulsed $\overline{\mathrm{H}}$ source

AEgIS Physics timeline

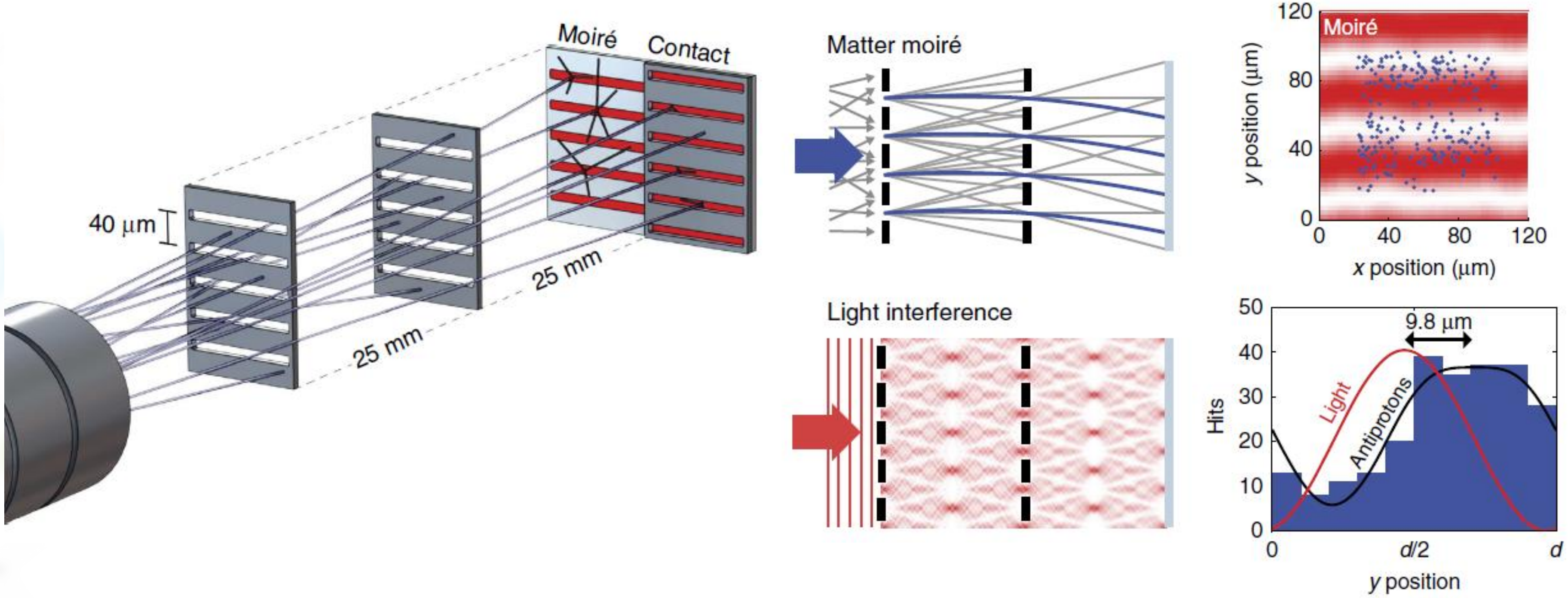


Main experimental results obtained during the AEgIS Phase 1

- Validation of the inertial sensing methodology with antiprotons
- Ps excitation to Rydberg levels in strong magnetic fields
- First pulsed antihydrogen source demonstration

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

A moiré deflectometer for antimatter



Key findings

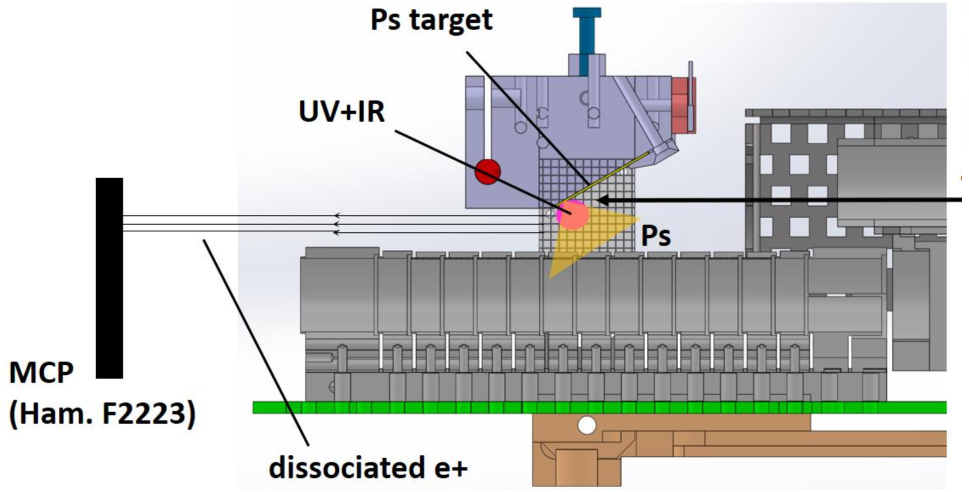
- Talbot-Lau interferometry is a effective tool for gratings alignment in 3D
- Near-field interference provides an undeflected reference
- aN sensitivity with 100 keV antiprotons and emulsion detectors

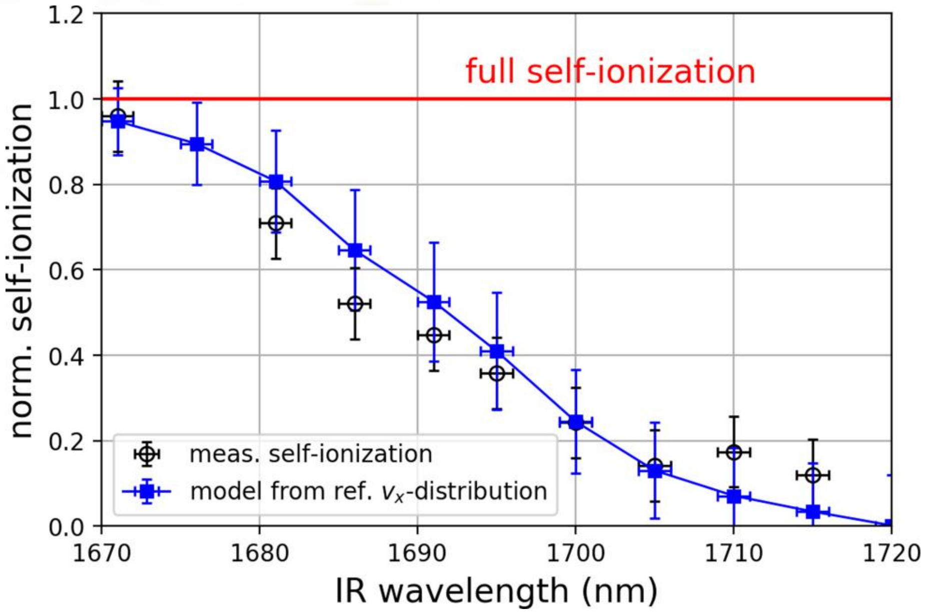
$$\Delta y = \frac{F_{\|}}{m}\tau^2 \longrightarrow F_{min} \approx 5 \cdot 10^{-16}\,\mathrm{N}$$

Ps excitation to Rydberg levels in strong magnetic fields

PHYSICAL REVIEW A **102**, 013101 (2020)

Rydberg-positronium velocity and self-ionization studies in a 1T magnetic field and cryogenic environment





Key findings

- Positronium excited to n = 15 – 17 in a 1T magnetic field
- Rydberg Ps **self-ionizes** due to the **motional Stark electric field**
- Limiting factor: Ps cannot be excited at higher levels than n = 17

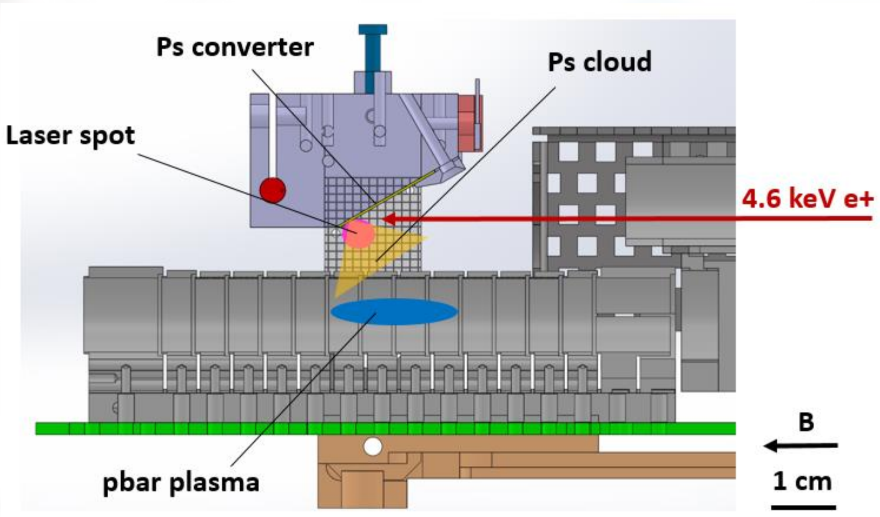
$$\vec{E}_{MS} = \vec{v} \times \vec{B} \approx 0.5 \div 1\ kV\ cm^{-1}$$

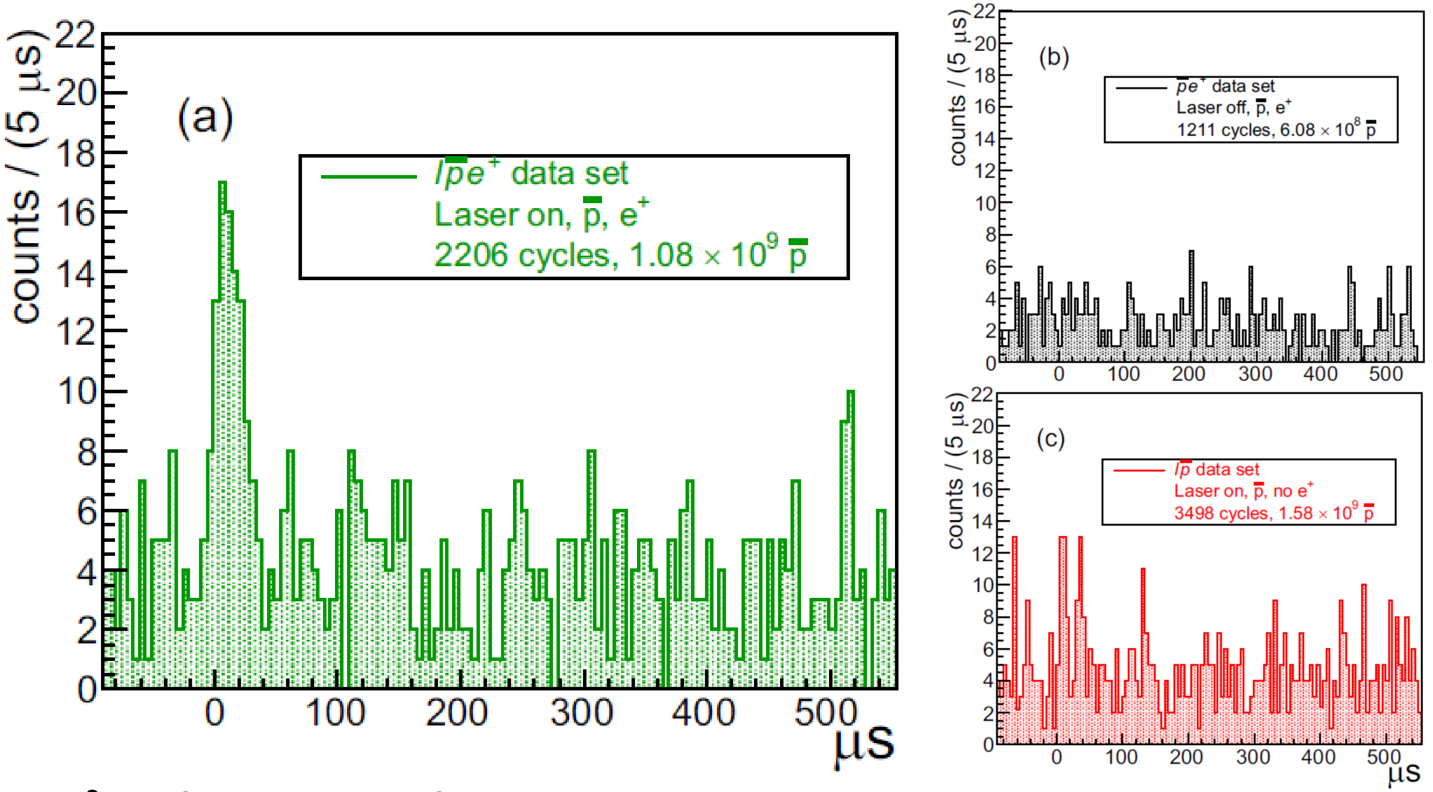
$$n_{\max} = \sqrt[4]{\frac{1.3 \cdot 10^{11}}{9vB\sin\theta}}$$

A first pulsed source of Rydberg antihydrogen

https://doi.org/10.1038/s42005-020-00494-z OPEN

Pulsed production of antihydrogen





Key findings

- 0.05 $\bar{H}^*$ produced per cycle (110 s) with 10^6 antiprotons and n = 17 Ps*
- Initial temperature of the antiproton plasma in the asymmetric trap of 400 K
- **Unexpectedly long 25 us bunch**: currently no explanation for this effect

Published with FELLINI

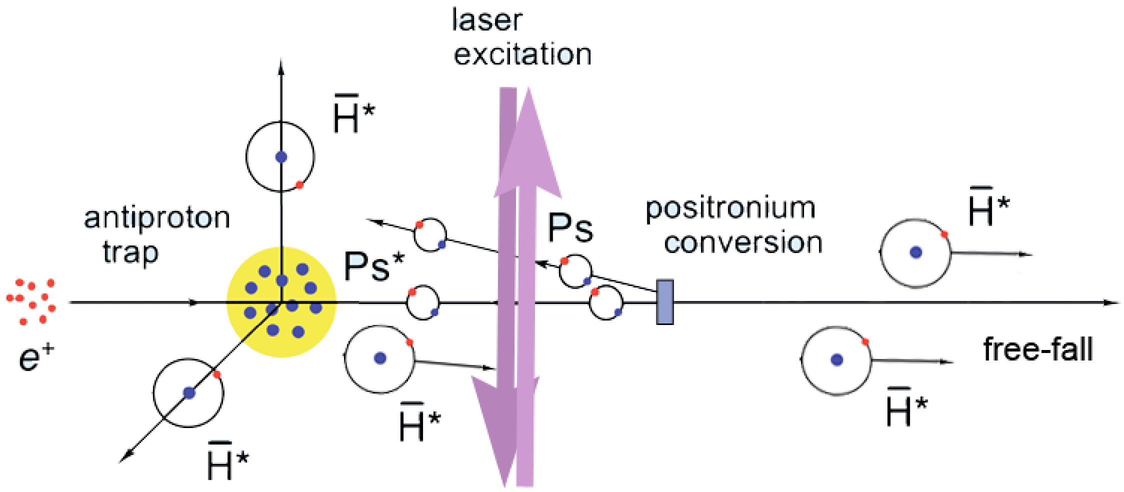
Main goal of AEgIS Phase 2: a first proof-of-concept inertial measurement with pulsed antihydrogen

Take-home messages from the AEgIS Phase 1

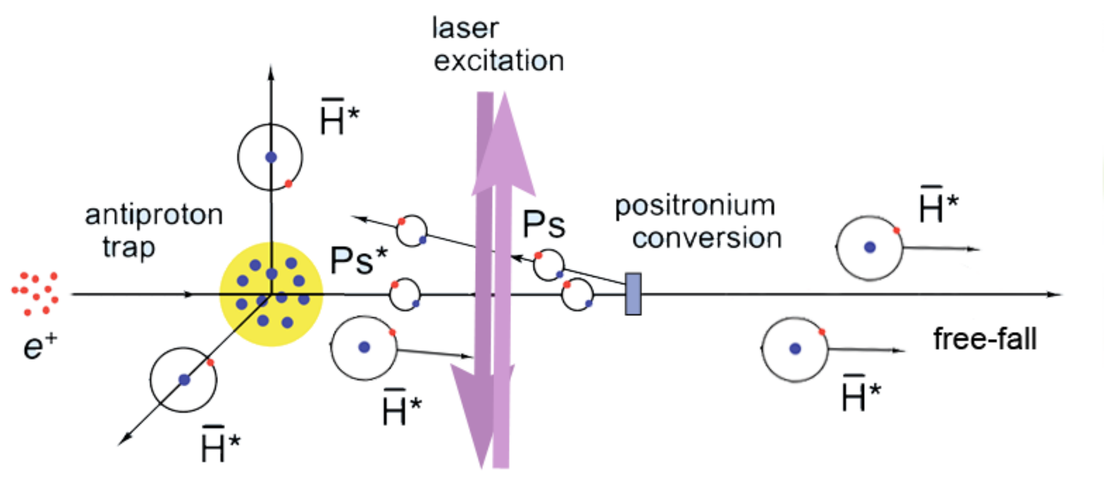
- The antihydrogen source intensity must be increased by 2/3 orders of magnitude
- The temperature of the produced atoms must be reduced by 1 order of magnitude
- The first gravitational measurement has to be designed to use Rydberg antihydrogens
- The free-fall should take place in the most homogeneous volume of the AEgIS magnet

New AEgIS Phase 2 configuration

- Positronium conversion target on-axis
- Laser excitation in a Doppler-free scheme
- Positrons passing through resting antiprotons



A closer look to the new experimental scheme



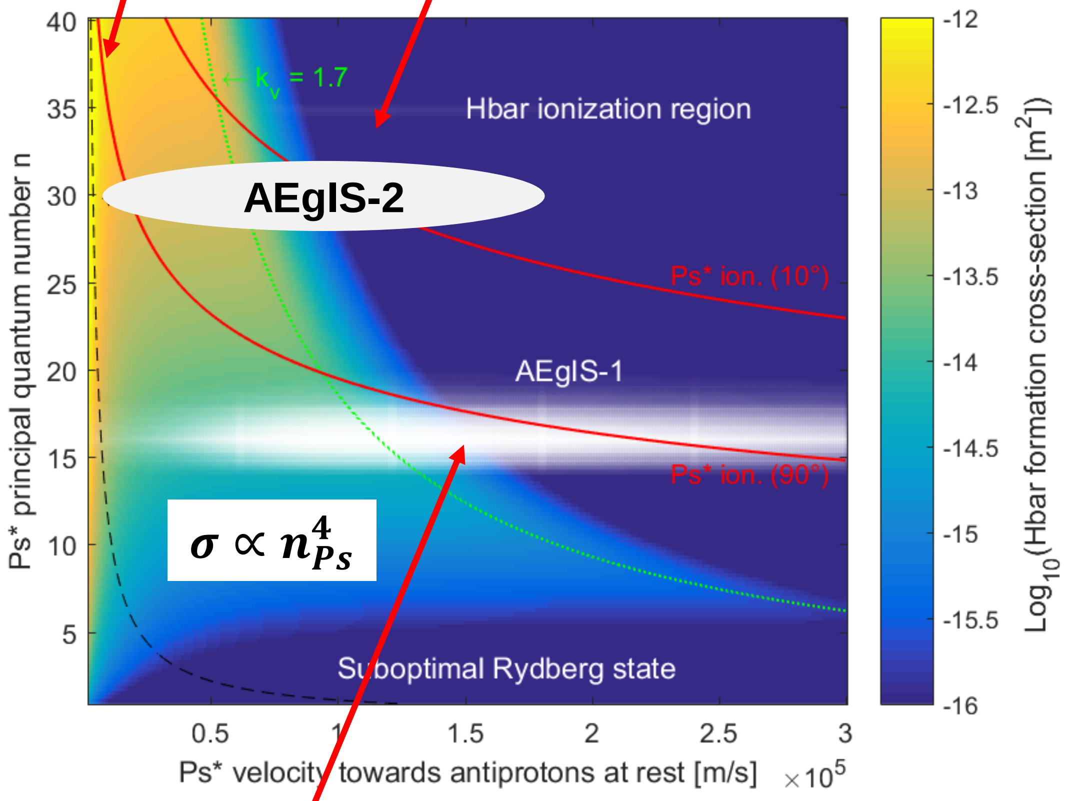
The way to a higher production cross-section

- Motional Stark effect is cancelled at first order
- Rydberg levels as high as n = 35 are reachable
- No azimuthal asymmetry in the antiproton trap
- Bigger electrodes with smaller imperfections

Caveat: some heat transferred to the pbar plasma from the passage of the positron burst (small)

Limit from motional Stark ionization

AEgIS-2 target Ps* distribution [1]



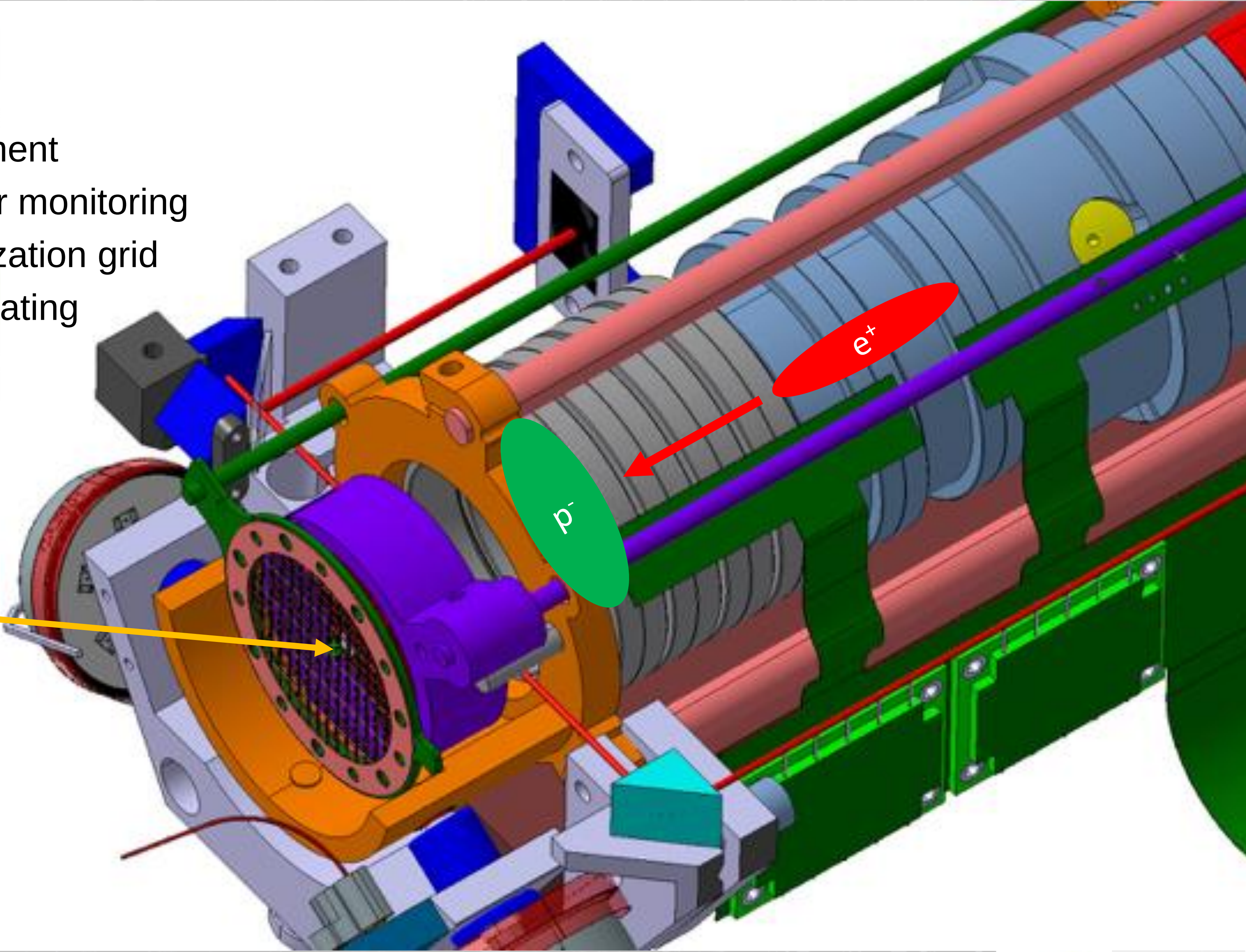
AEgIS-1 Ps* distribution

[1] S. Mariazzi et al., J. Phys. B (2021) 085004

AEgIS-2 trap redesign

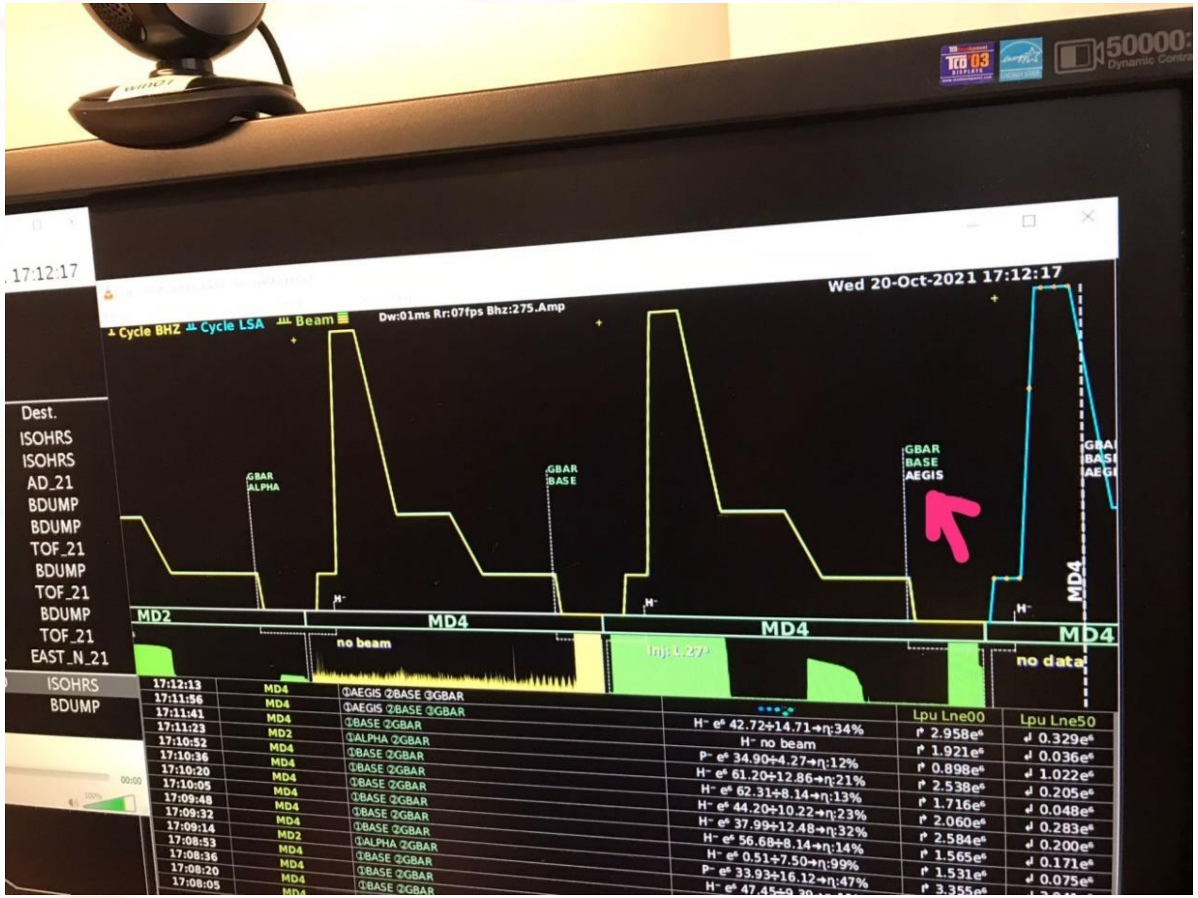
AEgIS-2 coaxial trap design

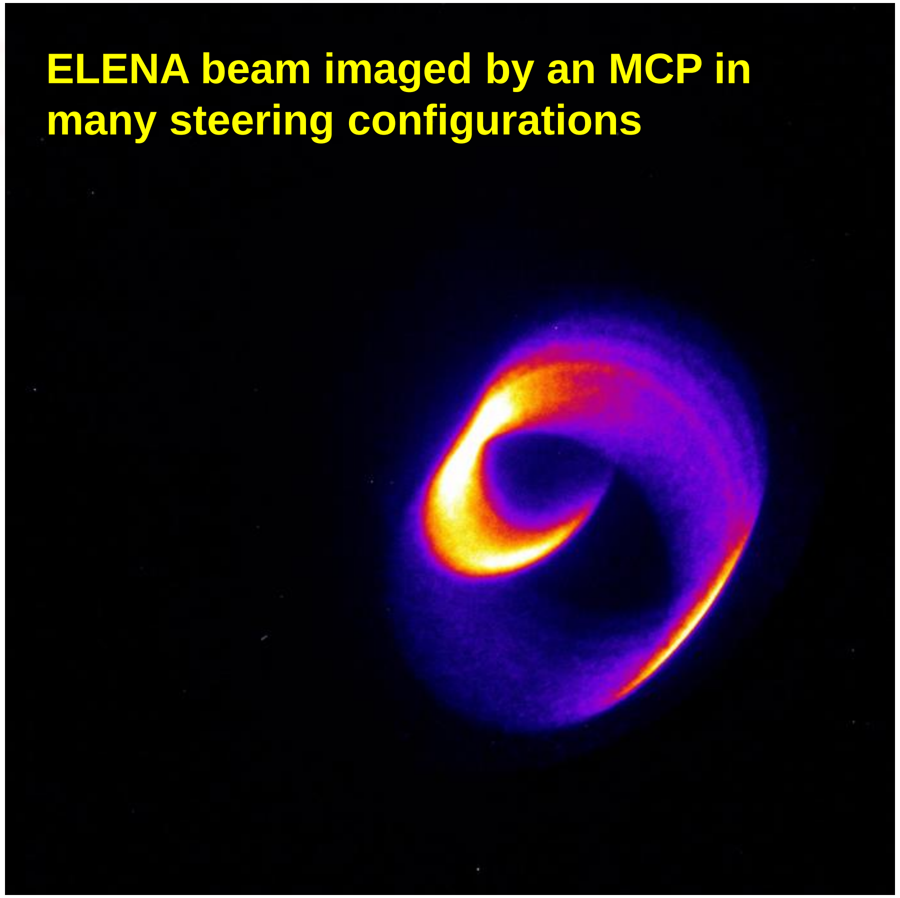
- Cryoactuators for B field alignment
- Double laser passage with fiber monitoring
- Movable target holder and ionization grid
- Cryofilters for minimal Joule heating



First antiprotons from ELENA in AEgIS

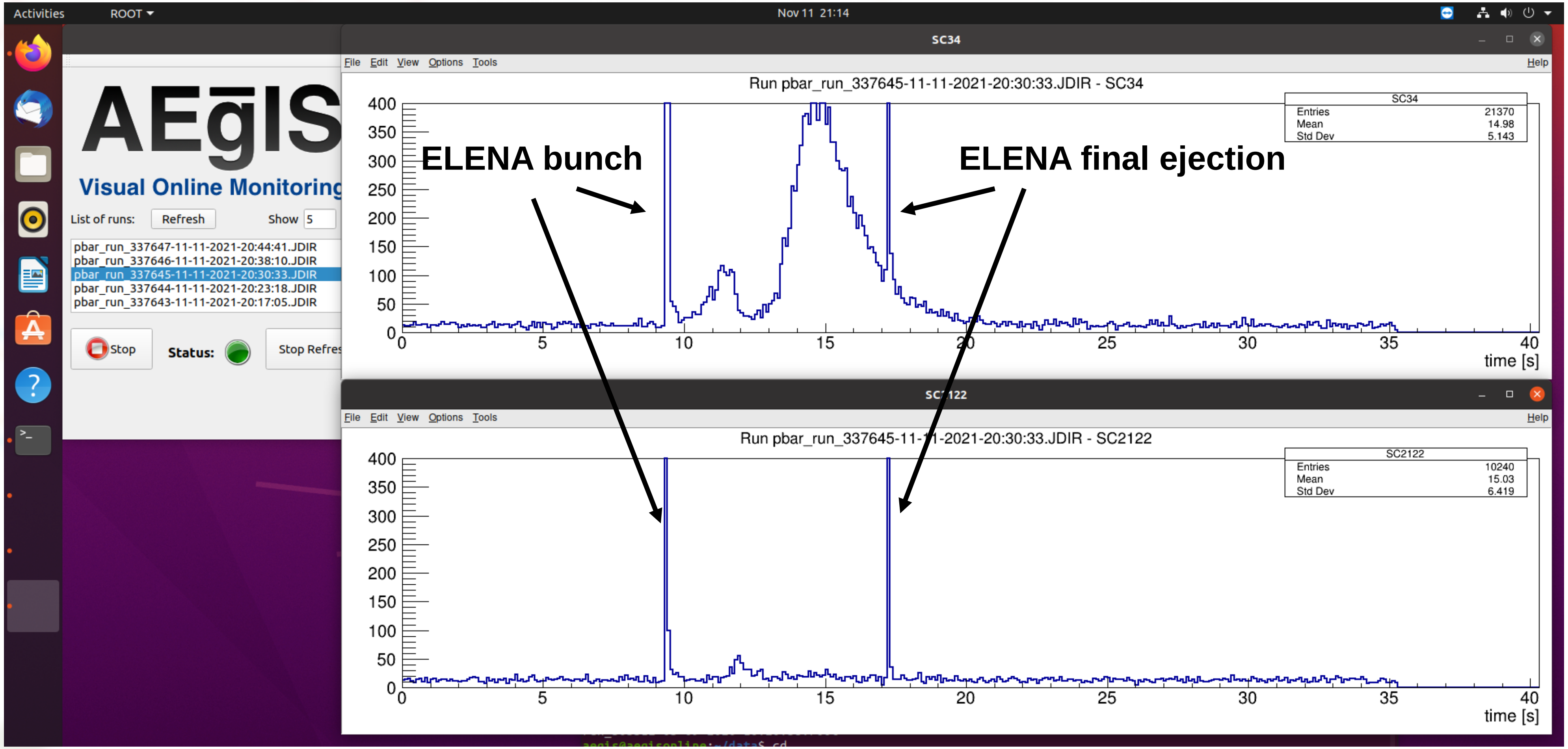
Supervision of two PhD students (SH and MV)





First antiprotons from ELENA observed on 20 October, 2021

Capture of antiprotons



First antiproton from ELENA caught from AEgIS-2 on 11th of November, 2021

AEgIS Phase 2 timeline (COVID-corrected)

	2021	2022	2023	2024	2025
WEP test on a pulsed Rydberg Hbar beam					
Installation and test of new trap electrodes					
Connection to the ELENA beamline					
Improvement of the Hbar source flux					
Development of pulsed Hbar beam via trapped antiprotons					
Interaction of Hbar* with gratings					
Proof-of-concept inertial sensing with pulsed Hbar beam					

Summary

- Demonstration of a first pulsed source of $\overline{\mathrm{H}}^*$ — **ok**
- O(10^3) higher $\overline{\mathrm{H}}^*$ production rate
- Pulsed beam of low energy $\overline{\mathrm{H}}^*$
- Gratings design validation with a beam of Rydberg atoms ($\overline{\mathrm{H}}^*$, Ps^*, $\bar{\mathrm{p}}\mathrm{ion}$ ...)
- First attempt of the measurement!

work in progress (items 2–4)