Mesure gravitationnelle de l'antimatière

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A E ḡ I S collaboration

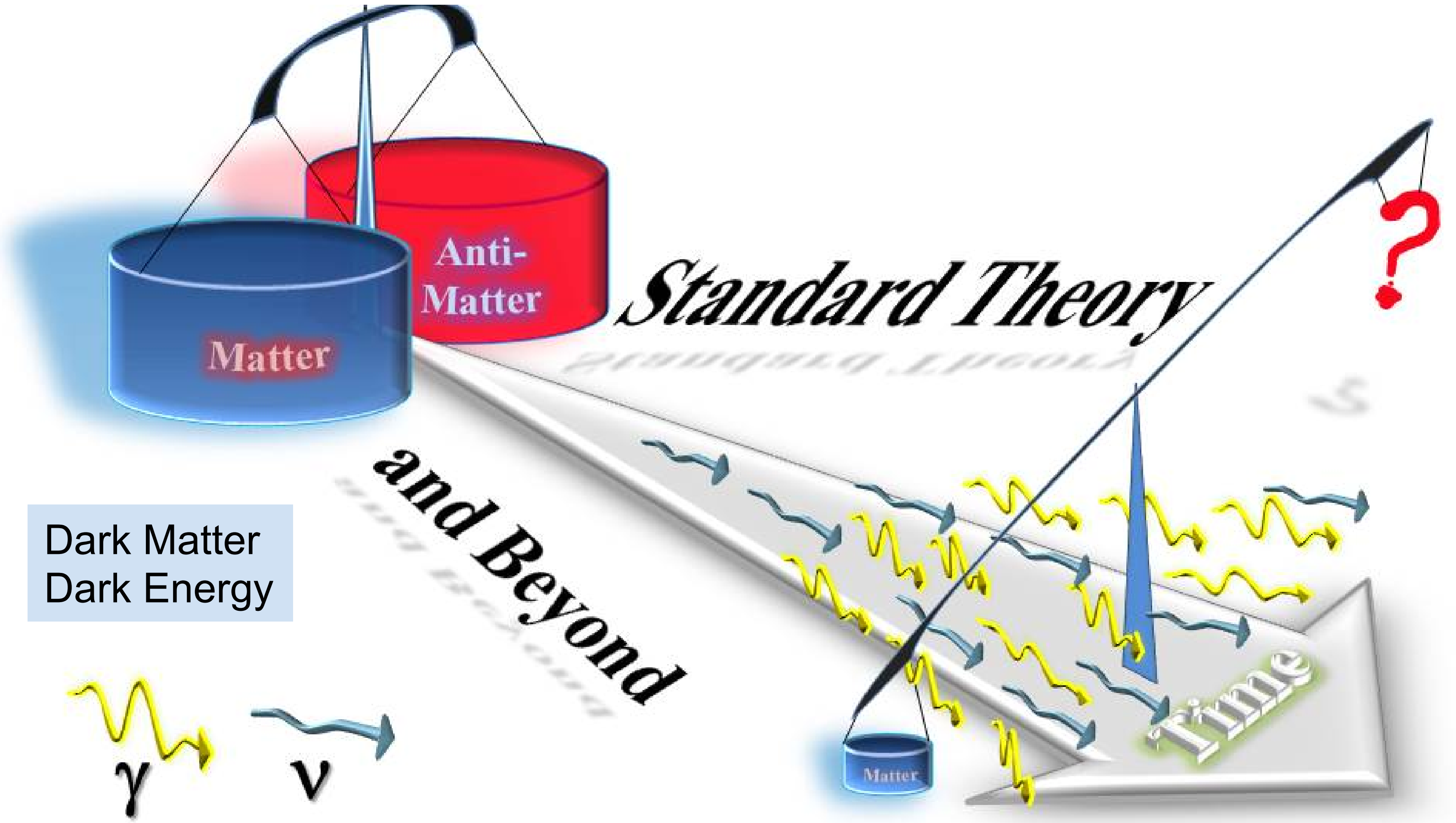
Stefan Meyer Institute	CERN	Czech Technical University	ETH Zurich
University of Genova	University of Milano	University of Padova	University of Pavia
Institute of Nuclear Research of the Russian Academy of Science	Max-Planck Institute Heidelbert	Politecnico di Milano	University College London
University of Bergen	University of Bern	University of Brescia	Heidelberg University
University of Lyon 1	University of Oslo	University of Paris Sud	University of Trento

INFN sections of: Genova, Milano, Padova, Pavia, Trento

Plan

- Motivations et buts
- Principe
- État de l’art
- Premiers résultats
- Futur proche - ELENA

Matière-Antimatière et Univers



L. Willmann, K. Jungmann arXiv:1506.03001

Antimatière & (anti ?) gravité

$$V = -G\frac{MM'}{r}\left(1 \mp a e^{-\frac{r}{v}} + b e^{-\frac{r}{s}}\right)$$

Newton

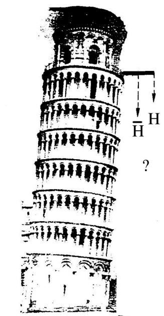
Supergravité N=2,..,8 : anti-graviton
-> gravité répulsive !

- Contraintes exp. : M. Nieto & al. Phys. Rep. 205 (1991)
- Motivation pour l' antigravité : G. Chardin, Hyp. Int. 109, 83 (1997)
- Violations de ~~Lorentz~~ & ~~CPT~~ : V.A. Kostelecky et al., Phys. Rev. D83 (2011)
- DM & DE : gravitation. pol. & dipole of vaccuum : D.S.Hajdukovic, Astro Space Sciences 338, (March 2012)

- Nouvelles expériences :
  - ALPHA (CERN-AD 2013) ; AEGIS (CERN-AD6 -2012) ; Gbar (CERN-AD 2016)

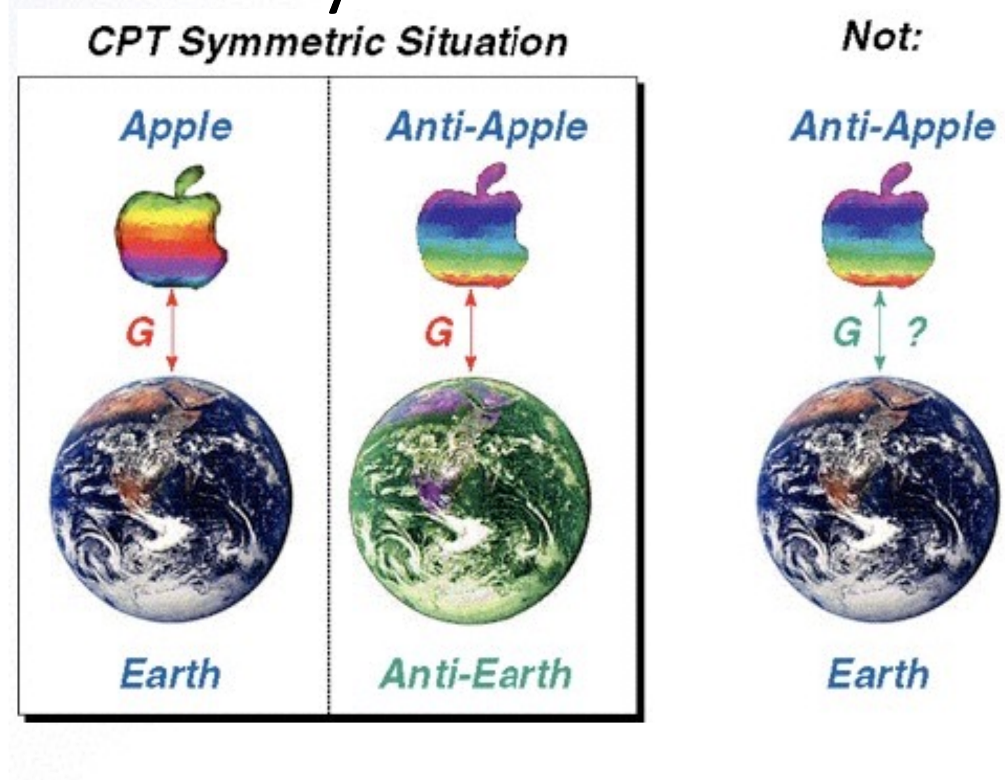
Goals and Motivations

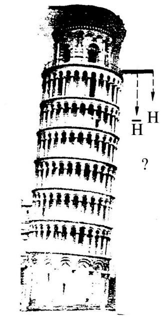
- Measure $\vec{P} = \overline{m} \times \vec{g}$ to 1%
  - Looking at free fall of cold $\overline{H}$ atoms
- Test of WEP on antimatter in the Earth gravitational field
  - First (?) direct measurement
  - Need a large number of atoms (10^5)
- Extra
  - Spectroscopy, Ps physics, H-Hbar comparison,…



Gravitational acceleration of antimatter

- No direct CPT test
  - Weak Equivalence Principle
- No precise experimental test yet
- Highest precision
  - With neutral antimatter

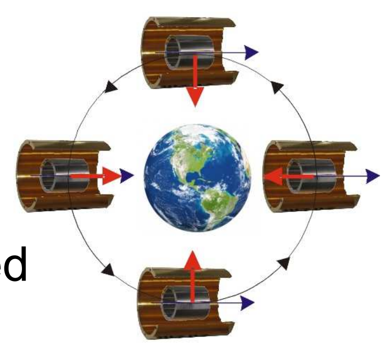




year	investigator	accuracy	method
500	Philoponus	"small"	drop tower
1585	Stevin	$5\ 10^{-2}$	drop tower
1590	Galileo	$2\ 10^{-2}$	pendulum,drop tower
1686	Newton	$1\ 10^{-3}$	pendulum
1832	Bessel	$2\ 10^{-5}$	pendulum
1910	Southerns	$5\ 10^{-6}$	torsion balance
1918	Zeeman	$3\ 10^{-8}$	torsion balance
1922	Eotvos	$5\ 10^{-9}$	torsion balance
1923	Potter	$3\ 10^{-9}$	pendulum
1935	Renner	$2\ 10^{-9}$	torsion balance
1964	Dicke et al	$3\ 10^{-11}$	torsion balance
1972	Braginski,Panov	$1\ 10^{-12}$	torsion balance
1976	Shapiro	$1\ 10^{-12}$	lunar laser ranging
1987	Niebauer et al.,	$1\ 10^{-10}$	drop tower
1989	Heckel	$1\ 10^{-11}$	torsion balance
1990	Adelberger	$1\ 10^{-12}$	torsion balance
1999	Baebler	$1\ 10^{-13}$	torsion balance
2016	Microscope	$1\ 10^{-15}$	space
20??		$1\ 10^{-18}$	space

expected

Equivalence Principle Tests for Matter systems



Limites indirectes

- Gravitational Clock Redshift for p/pbar

Gravitational red shift for a clock: $\Delta\omega / \omega = g\, h / c^2$

→ Antimatter and matter clocks run at different rates
if g is different for antimatter and matter

$$\frac{\Delta\omega_c}{\omega_c} = 3(\kappa - 1)\frac{U}{c^2}$$

for tensor gravity
(would be 1 for scalar gravity)

grav. pot. rnergy difference
between empty flat space time
and inside of hypercluster of galaxies

Hughes and Holzscheiter,
Phys. Rev. Lett. 66, 854 (1991).

Experiment: TRAP Collaboration, Phys. Rev. Lett. 82, 3198 (1999).

$$\frac{\Delta\omega_c}{\omega_{\partial c}} < 10^{-10} \quad --> \quad \kappa = 1 \pm \ (< 10^{-6})$$

Limites directes actuelles

- Antimatière
  - « Limites » ALPHA
    - Expérience de sédimentation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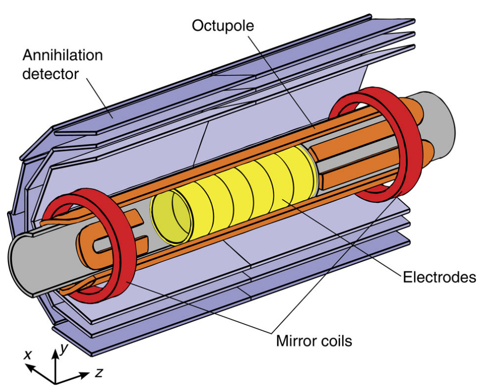
NATURE COMMUNICATIONS | ARTICLE OPEN

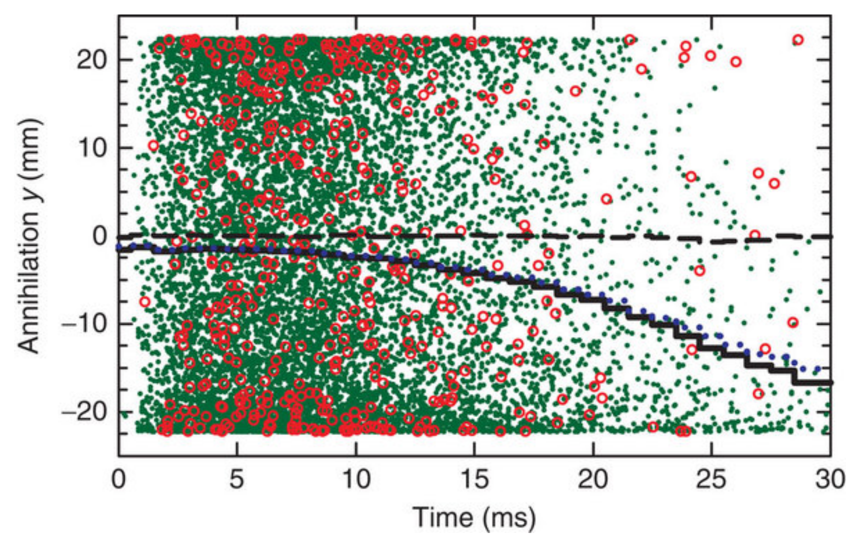
Description and first application of a new technique to measure the gravitational mass of antihydrogen

The ALPHA Collaboration & A. E. Charman

$$-65 < \frac{M_g}{M} < 75$$

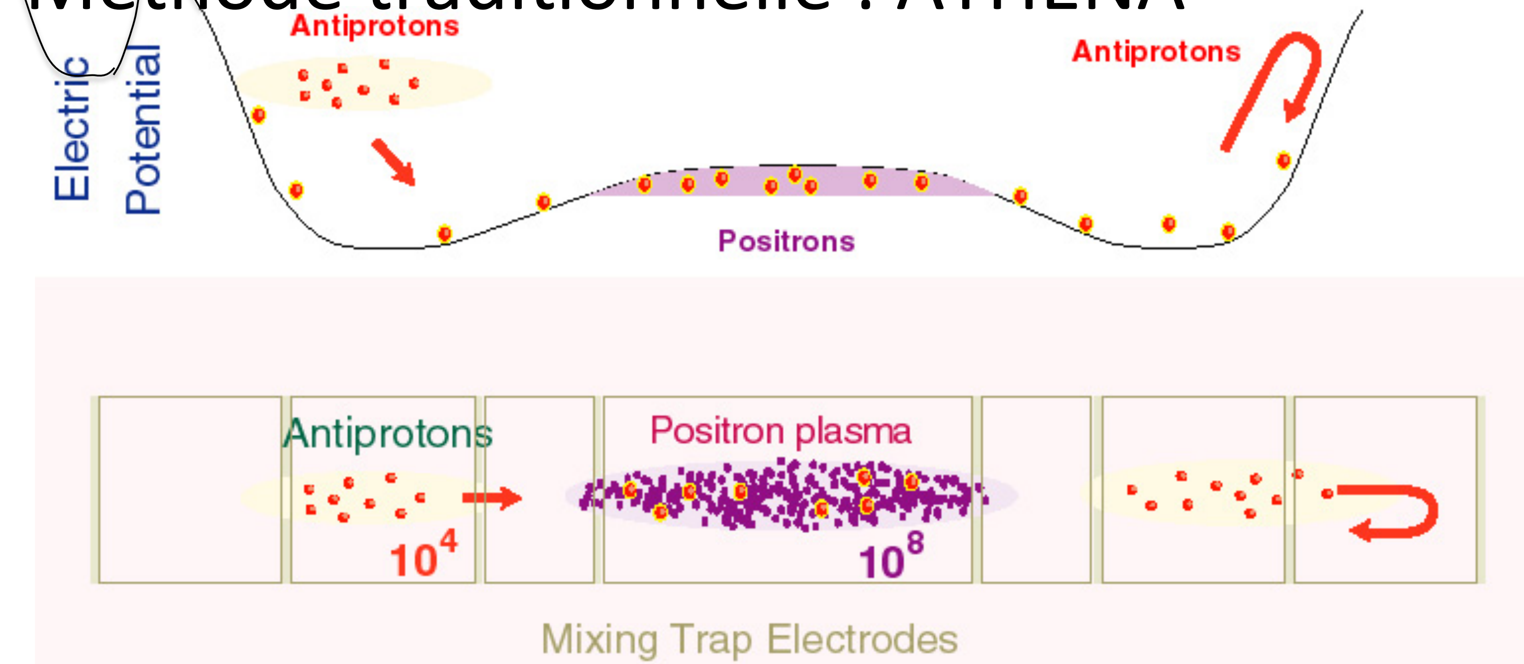
Pas de contrainte très forte !





Antihydrogène : production

- Méthode traditionnelle : ATHENA



a) Radiative recombination

$$\overline{p} + e^{+} \rightarrow \overline{H} + h\nu$$

Populate low n (n<10)

$$R \propto n_{e^+} T_{eff}^{-1}$$

b) 3 body recombination

$$R \propto n_{e^+}^{2} T_{eff}^{-9/2}$$

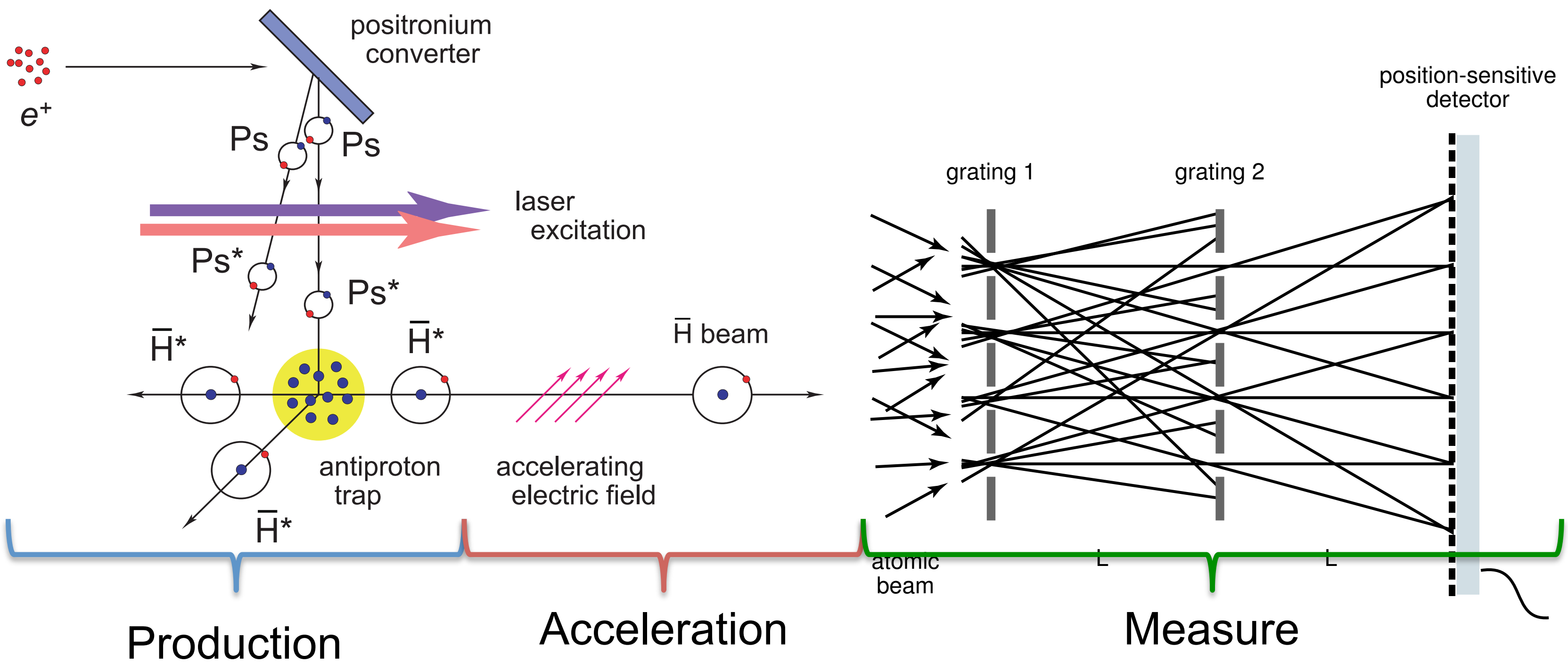
Populate high n, ionization by collisions and field ionization)

$$\overline{p} + e^{+} + e^{+} \rightarrow \overline{H} + e^{+}$$

Cold pbar : AEgIS recipe

$$\bar{p} + (Ps)^* \rightarrow \bar{H}^* + e^-$$

: Charge exchange reaction



AEgIS $\overline{\mathrm{H}}$ production way

$$\overline{\mathrm{p}} + (\mathrm{Ps})^* \rightarrow \overline{\mathrm{H}}^* + \mathrm{e}^-$$

- Antiprotons:
  - $\overline{\mathrm{p}}$ (5 MeV) from CERN AD
  - Degrade & keep E<10 keV
  - Cool down (5T trap)
- Positronium

$$\mathrm{Ps}^* = (\mathrm{e}^+\mathrm{e}^-)$$

  - e^+ on nano-porous SiO_2, Rydberg states (n)
- Form $\overline{\mathrm{H}}$ by interaction of Ps with $\overline{\mathrm{p}}$ cloud
  - Xsection: $\sigma \propto n^4$

AEgIS H production way

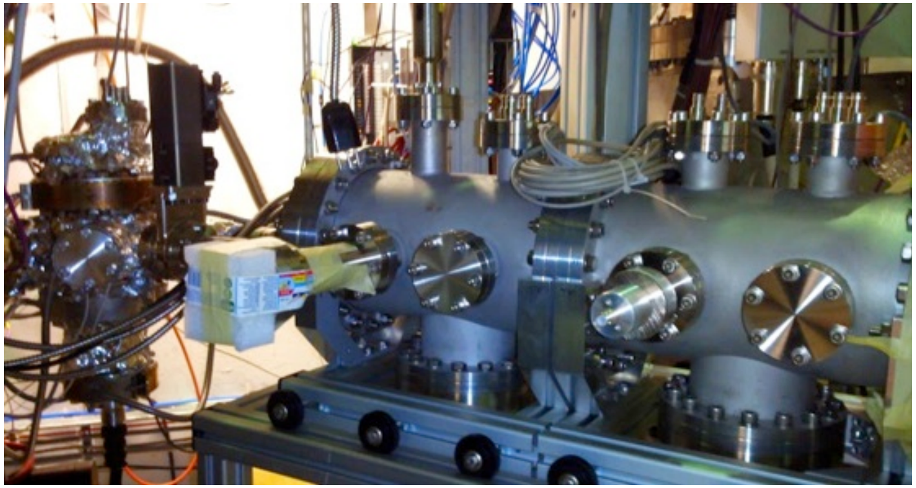
- Adding a p beam gives C-conjugate:
  - p (2 keV)

$$p + (Ps)^* \rightarrow H^* + e^+$$

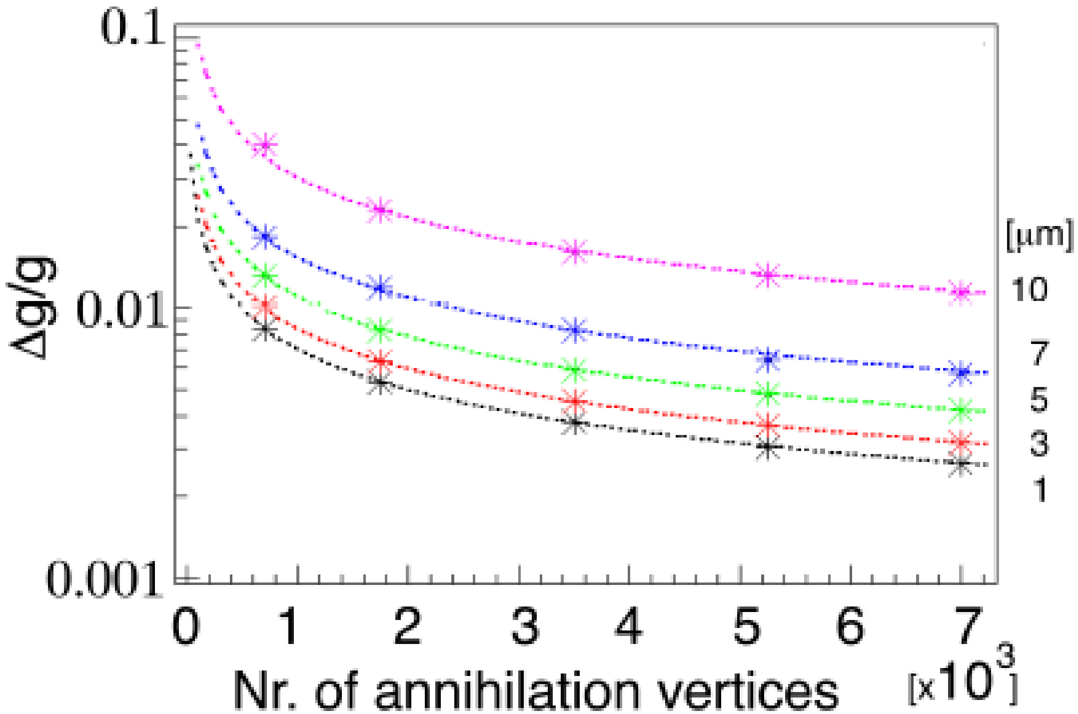
- Form H by interaction of Ps with p cloud

$$Ps^* = (e^+ e^-)$$

- Comparison H-Hbar
- Extra needs
  - P beam, H-detector
  - Installed in 2014

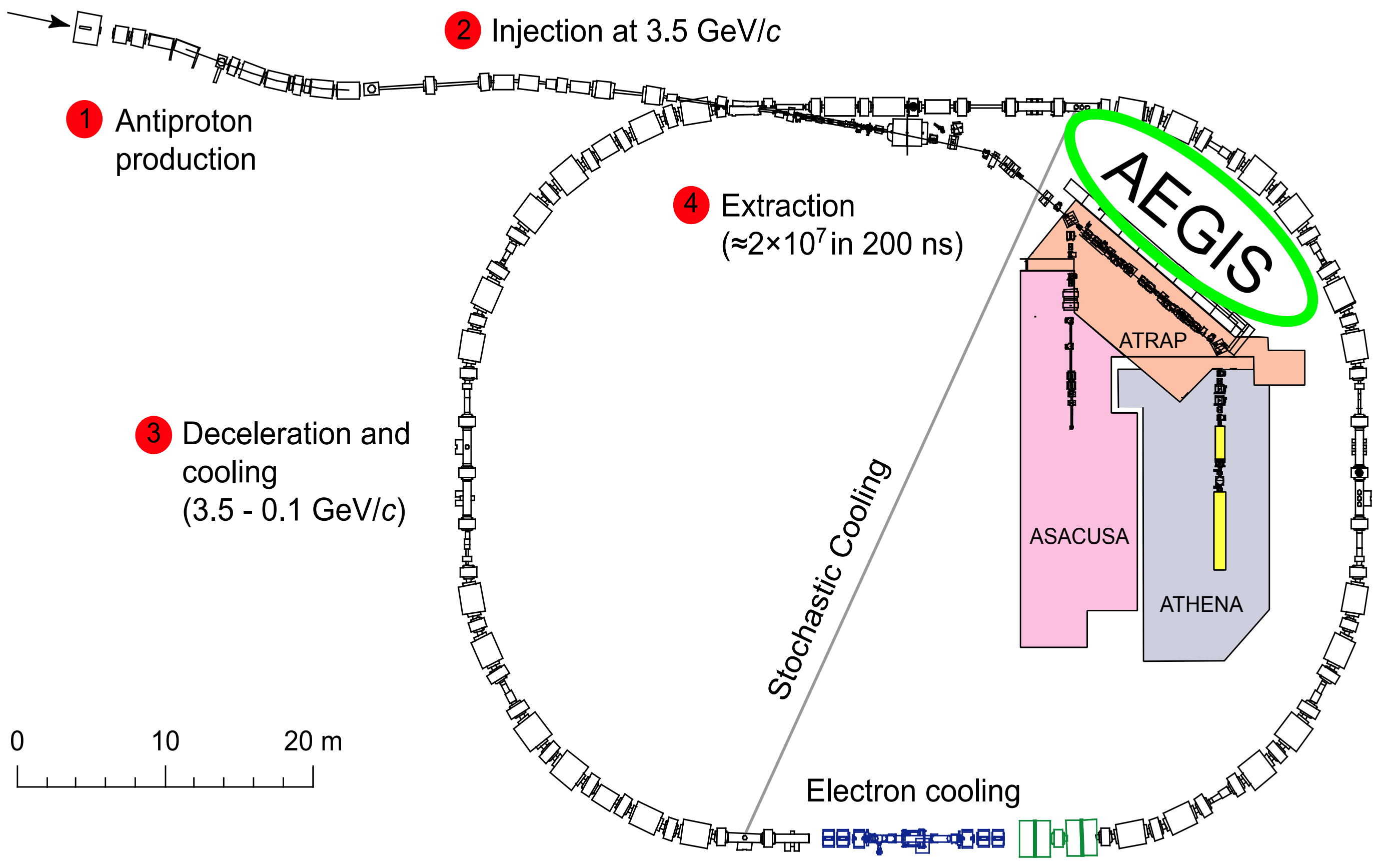


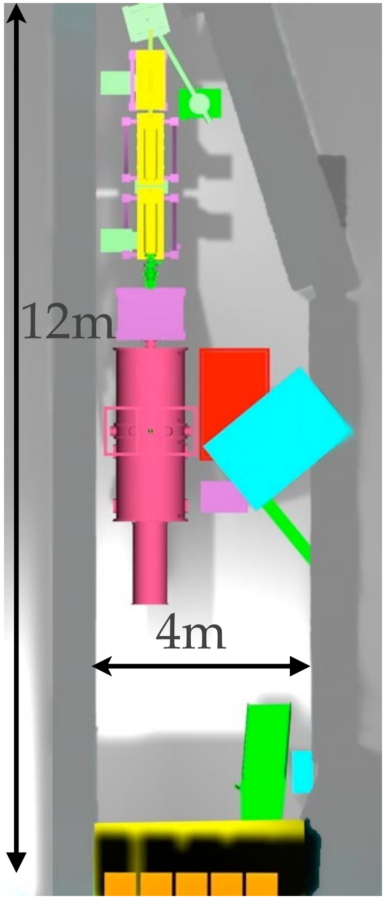
Measurement sensitivity



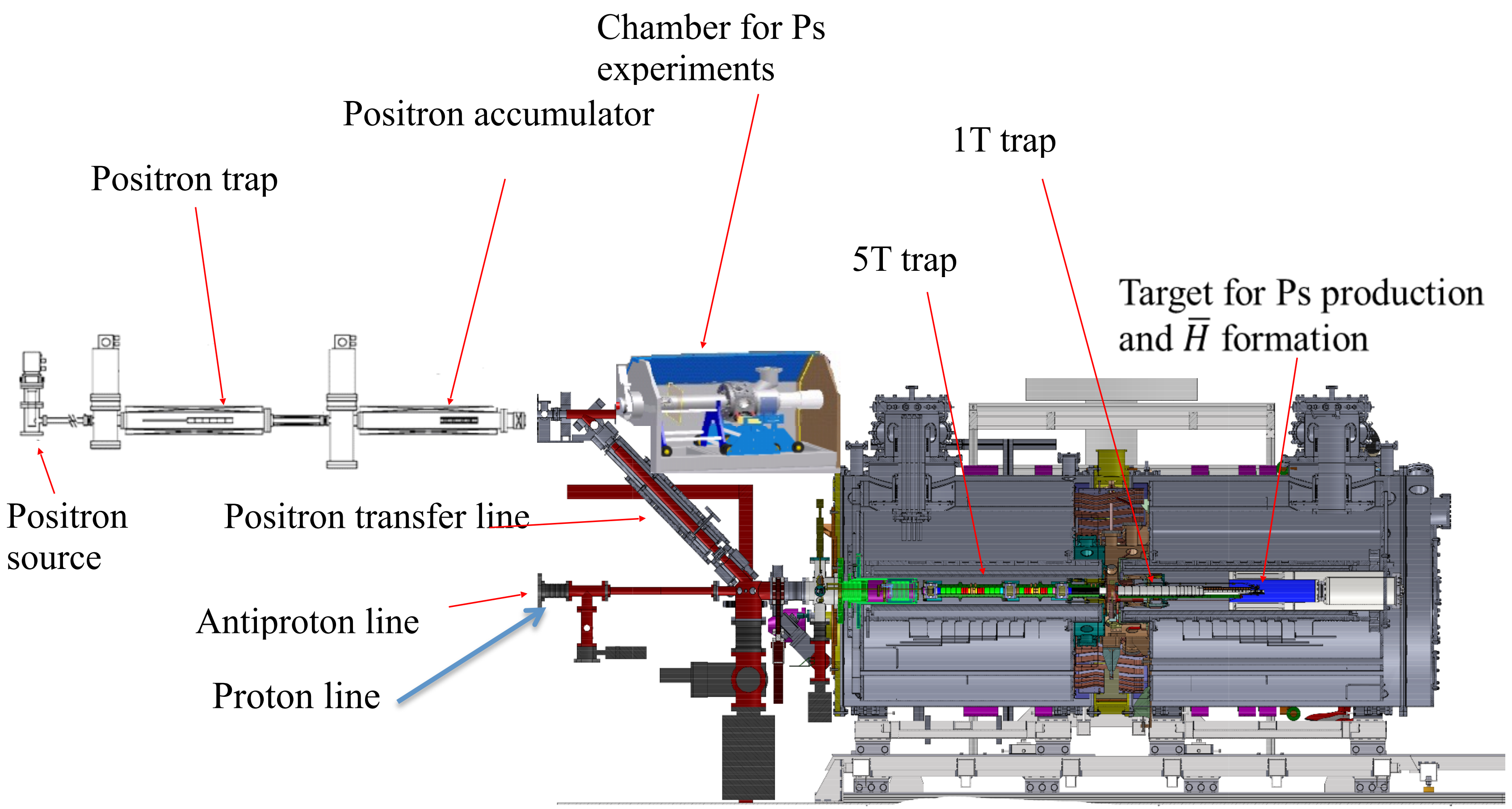
- 1% sensitivity achievable with ~ 600 annihilations
- Measurement resolution ~ 3 μm
- Cold antihydrogen necessary for bigger deflection and lower beam divergence.

Experimental site
CERN Anti Decelerator(AD) area

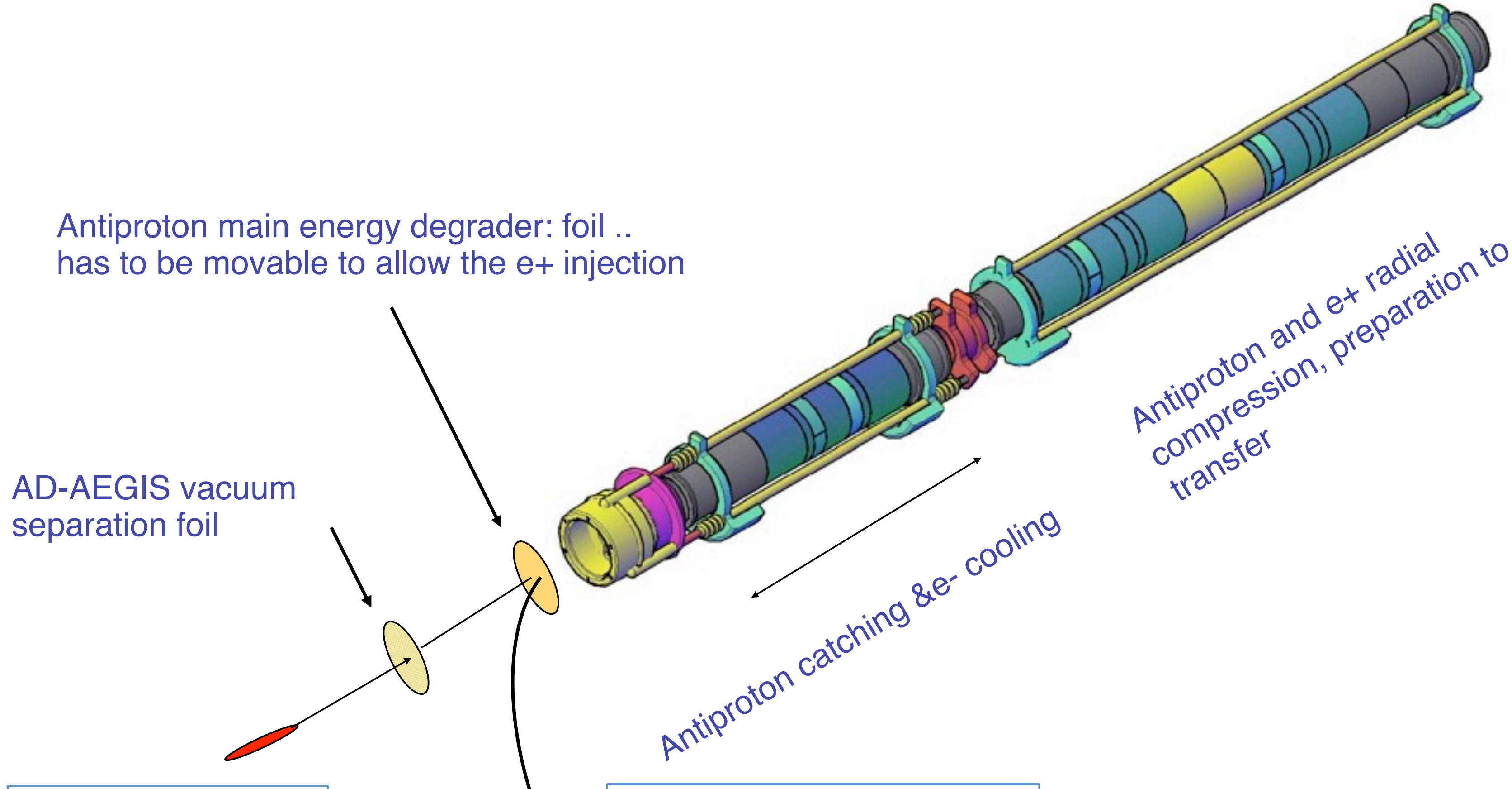




Experimental setup



pbar degrader



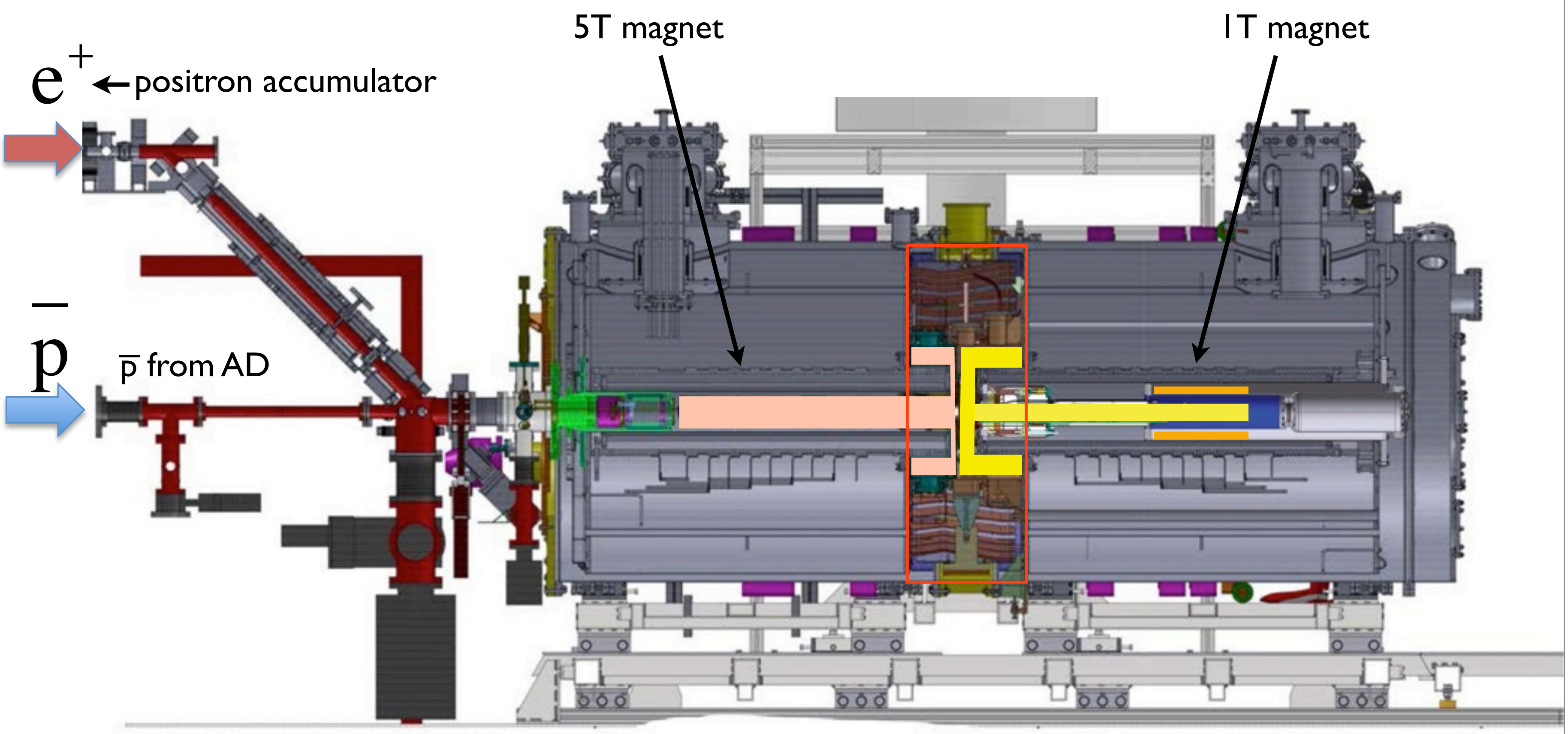
5300 keV pbar
3 10^7/ shot

Keep < 10 Mev pbar
~40 000/shot

Apparatus

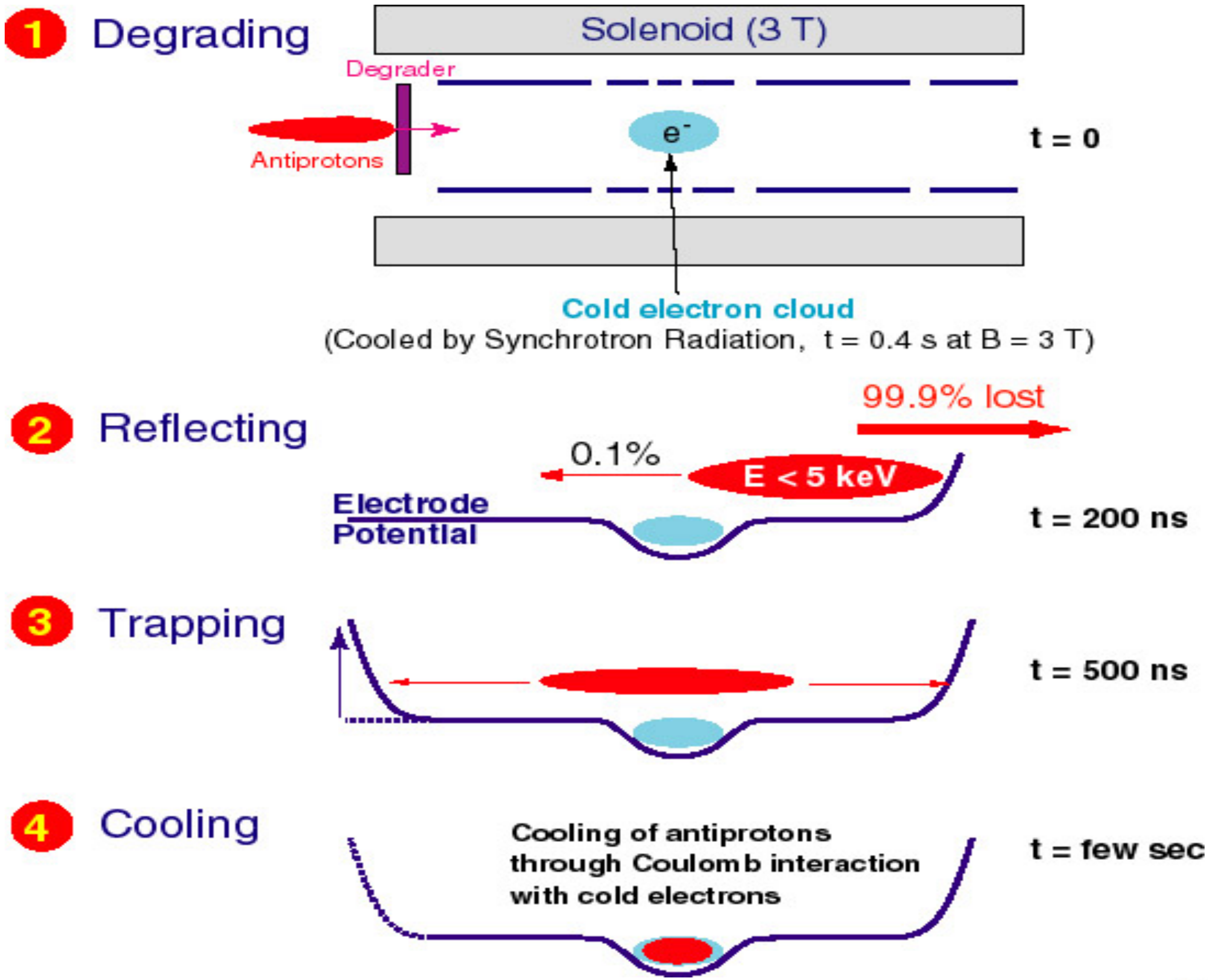
Pbar catching & Cooling
E+ storage (T~10K)

p-pbar cooling
Ps prodiction
H-Hbar production

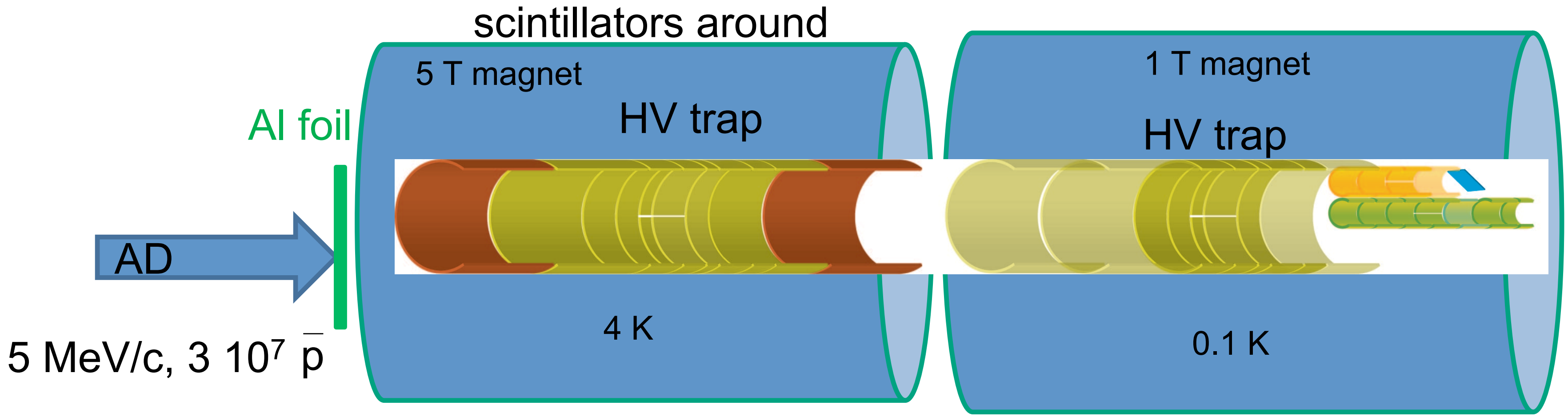


CERN AD area

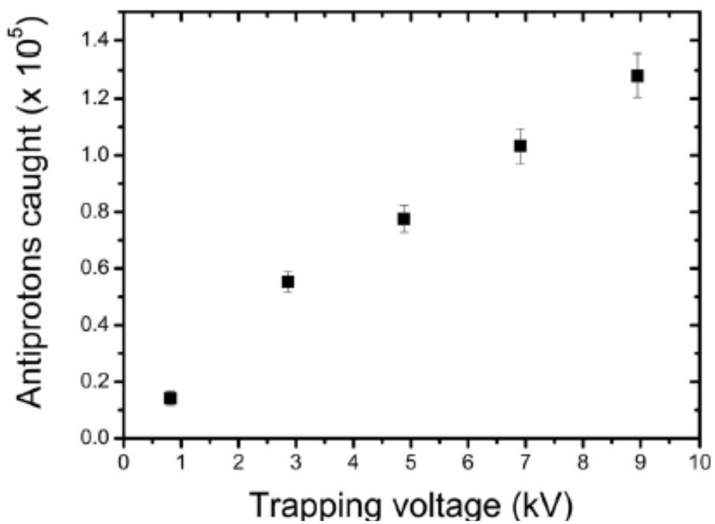
Trapping antiprotons



Antiproton trapping

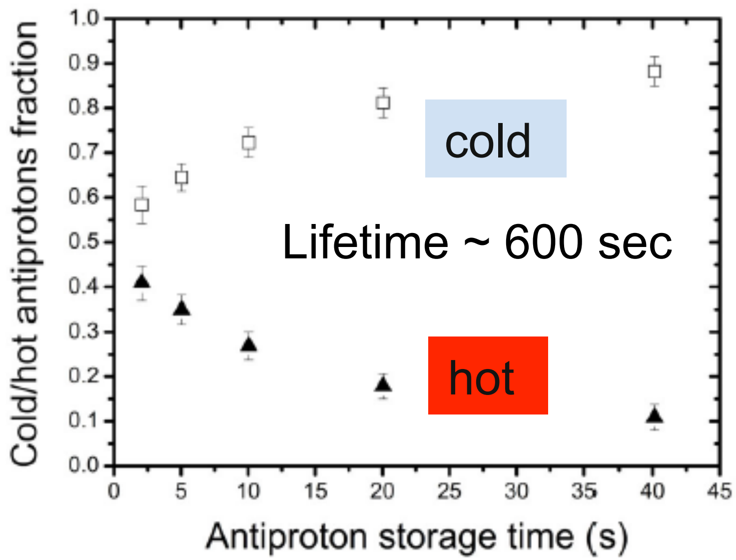


Anti-p catching after Al degrader in the 5T trap



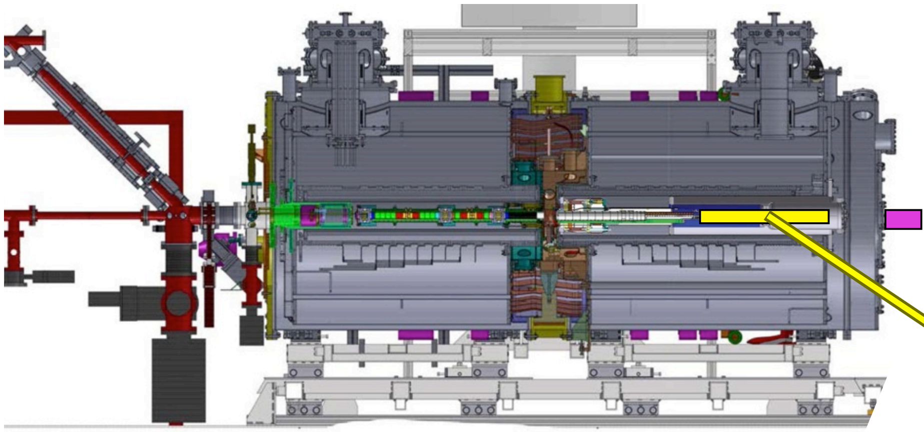
D. Krasnický *et al.,* AIP Conf. Proc. 1521, 144 (2013)

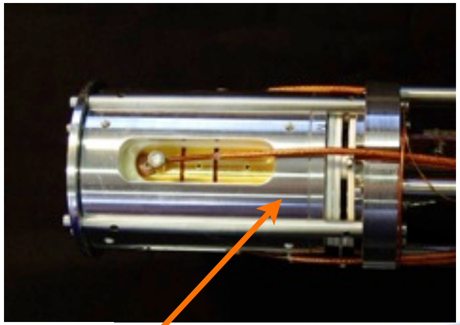
Cooling by electrons

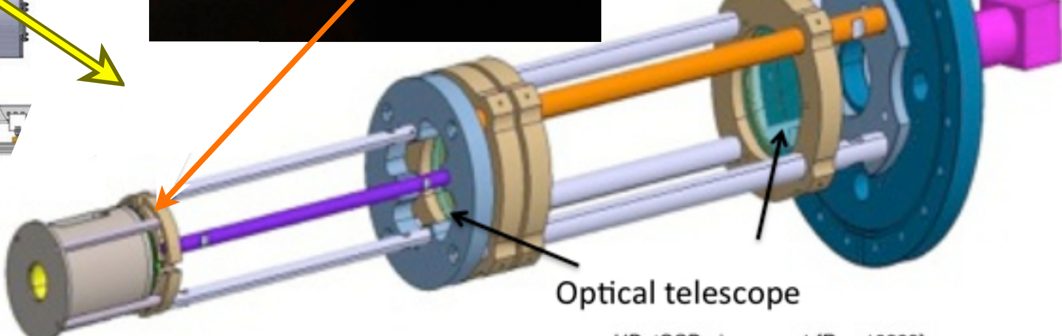


(anti)hydrogen detector

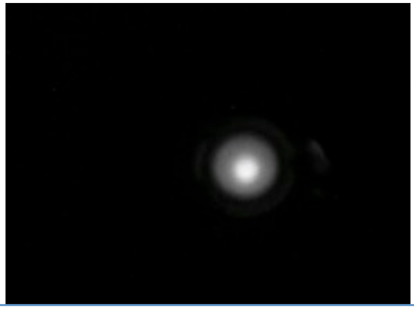
- Tune/Analyse traps

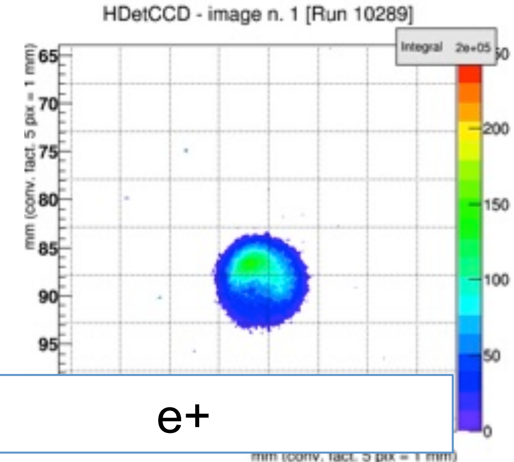






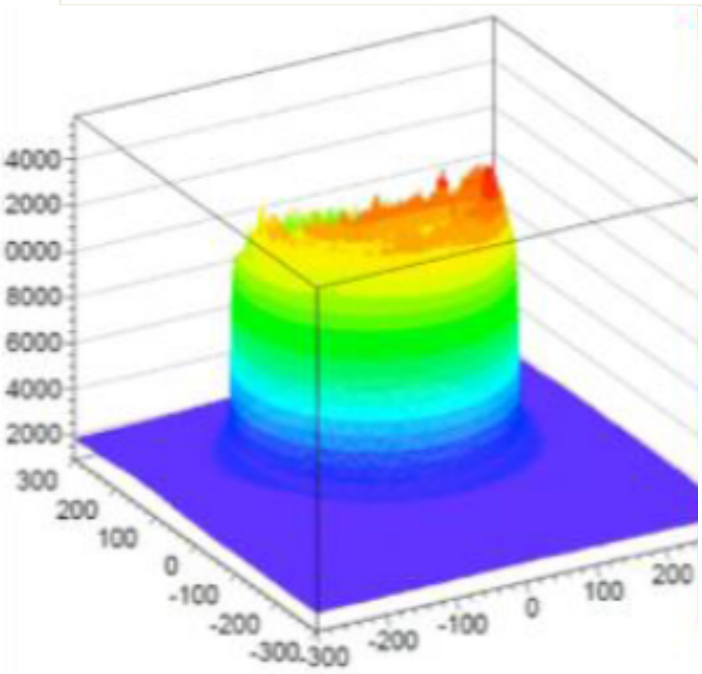
field-ionizing electrodes + MCP / Faraday cup + optics + CCD camera

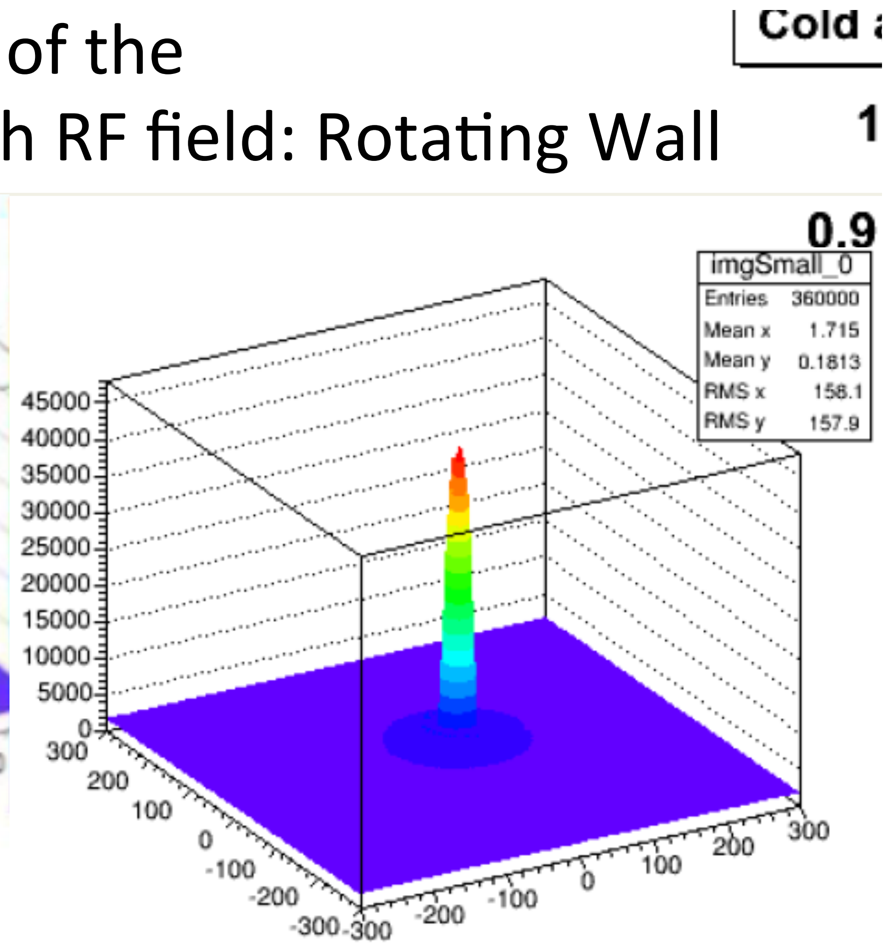




Commissioned (2014) with e-, pbar, e+

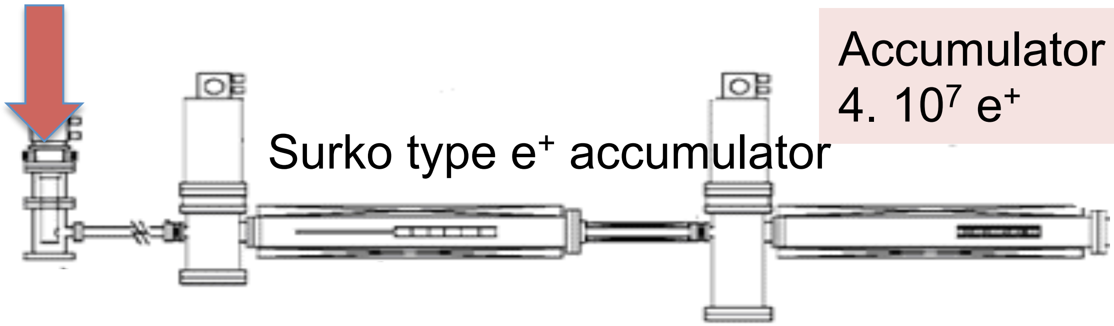
Radial compression of the Trapped plasma with RF field: Rotating Wall





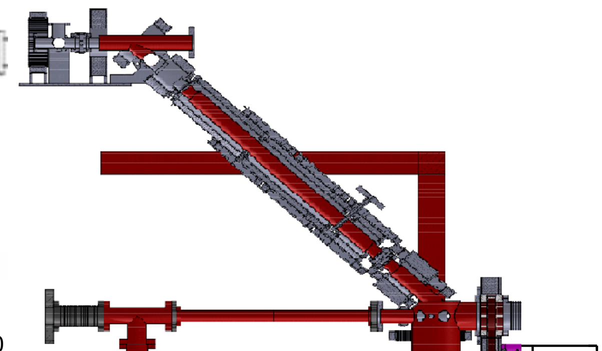
Positrons line

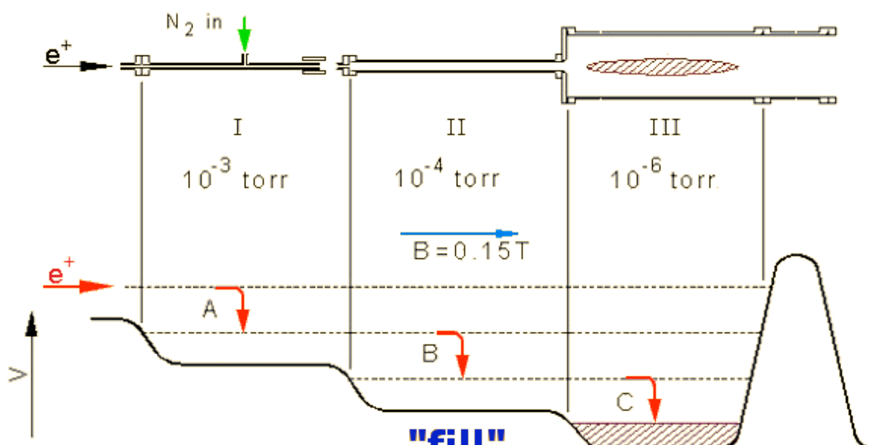
^{22}Na (14 mCi)
Solid Ne moderator: $\varepsilon = 2.10^{-2}$
Trapping: $\varepsilon = 0.14$



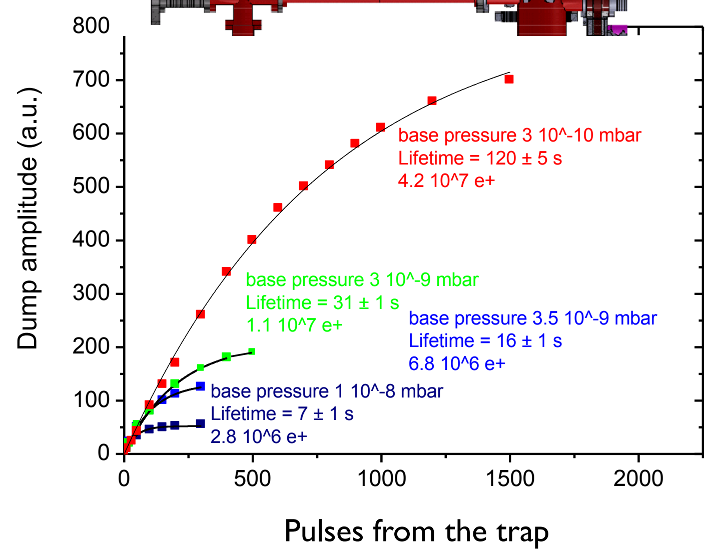
Accumulator
4. 10^7 e$^+$

Transfer line
$\varepsilon = 0.9$



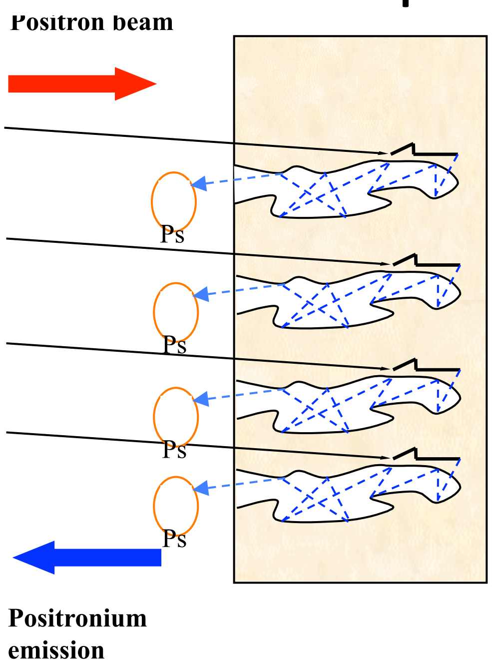


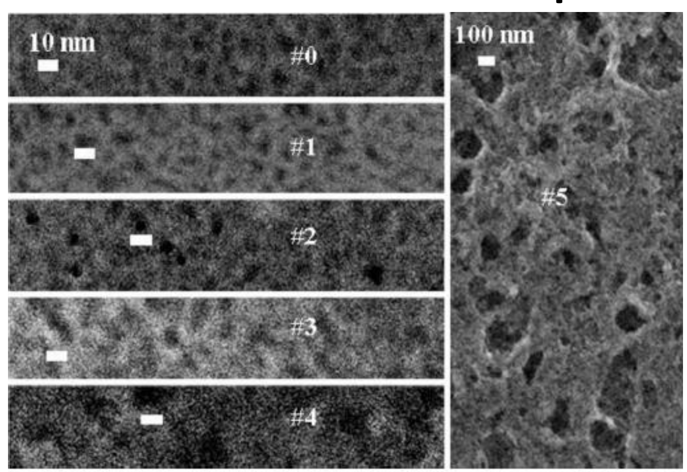
- ^{22}Na source: > 50 -100 mC
- Moderation through solid neon
- Accumulation in trap
- Buffer gas cooling



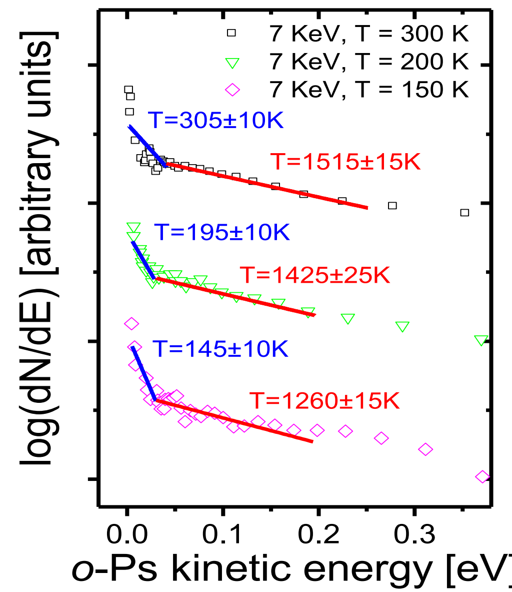
Positronium formation

- Implantation of e^+ in nano-porous target
  - SiO_2 - 8-14 nm pores;T~75 K oPs
  - Tune pore size to tune Ps temp.





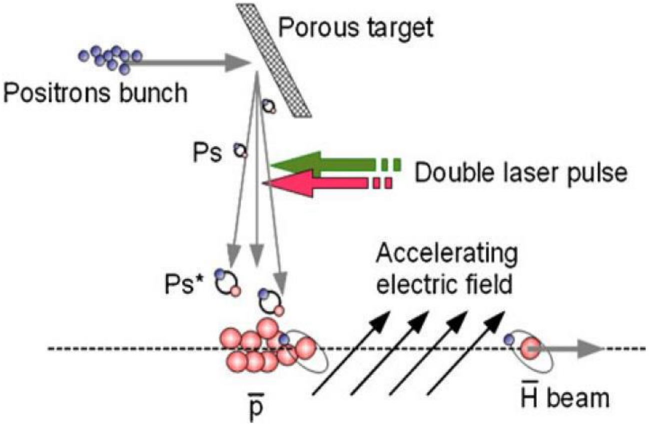
Nanochannels size
0 : 4 – 7 nm   # 3 : 10 – 16 nm
1 : 8 – 12 nm   # 4 : 14 – 20 nm
2 : 8 – 14 nm   # 5 : 80 – 120 nm

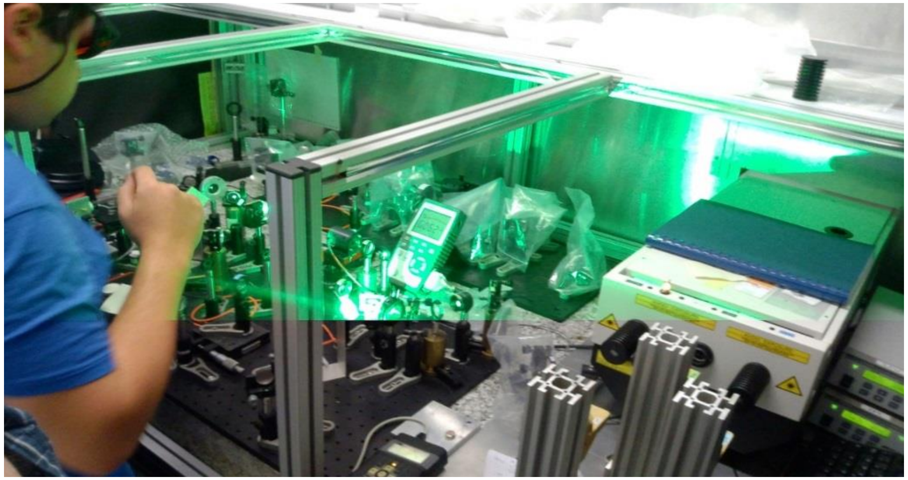


S. Mariazzi et al., Phys. Rev. B 78, 085428 (2008)
S. Mariazzi et al., Phys. Rev. B 81, 235418 (2010)

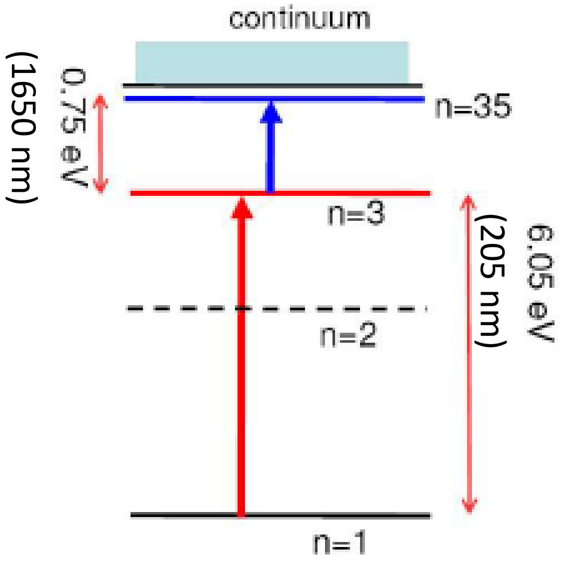
Ps excitation

- Two stages excitation
  - UV (205 nm): n=1$\rightarrow$ 3
  - IR (1650-1700 nm): n=3 $\rightarrow$25-3



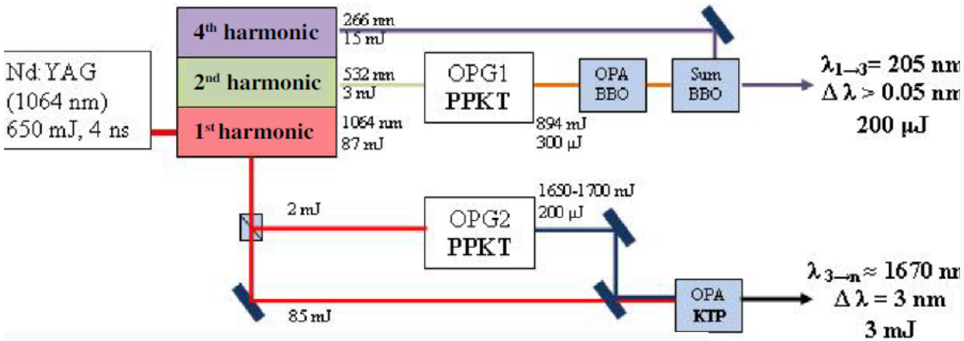


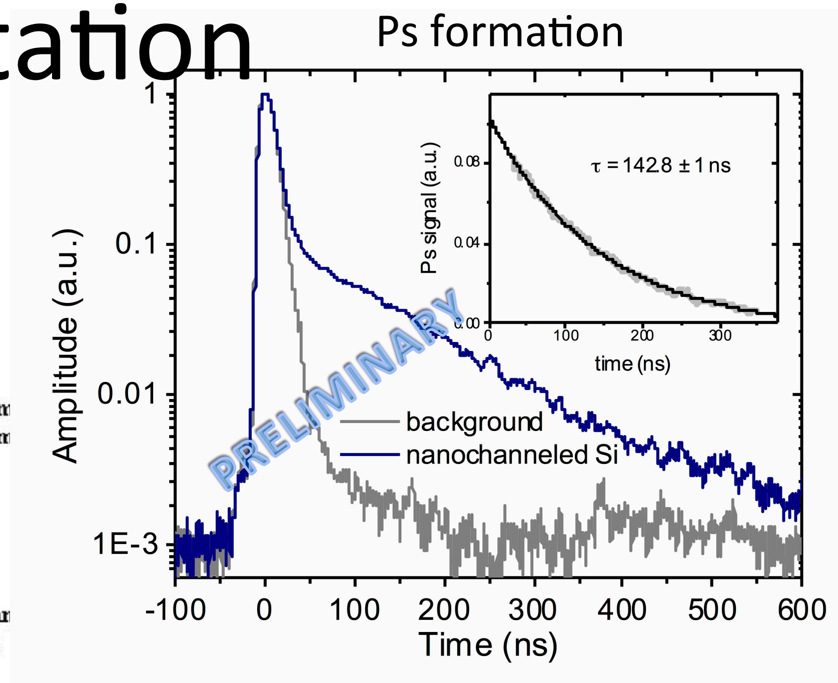
Phys. Rev. A 78 (2008) 052512; NIM B 269 (2011) 1527

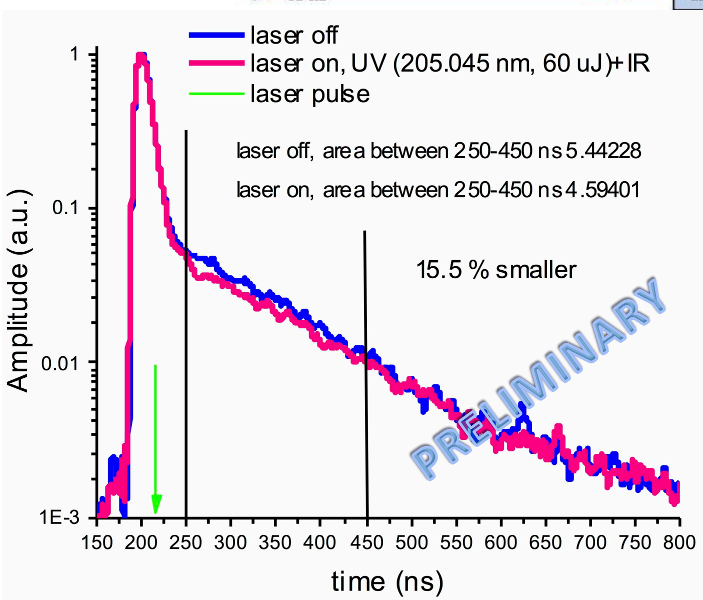


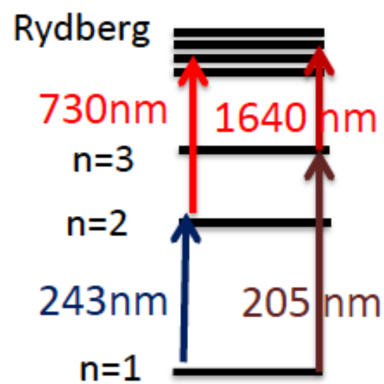
Ps excitation

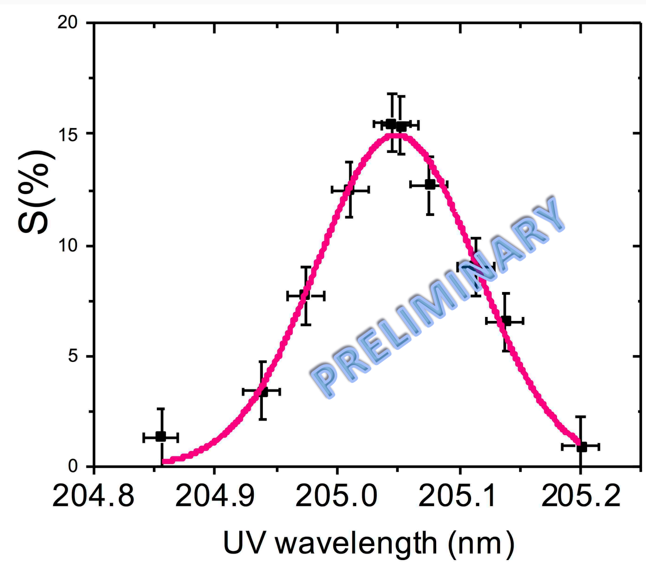
- Test on Ps formation & excitation in a separate breadbox
- Laser excitation to n=3 demonstrated by photoionization measurements



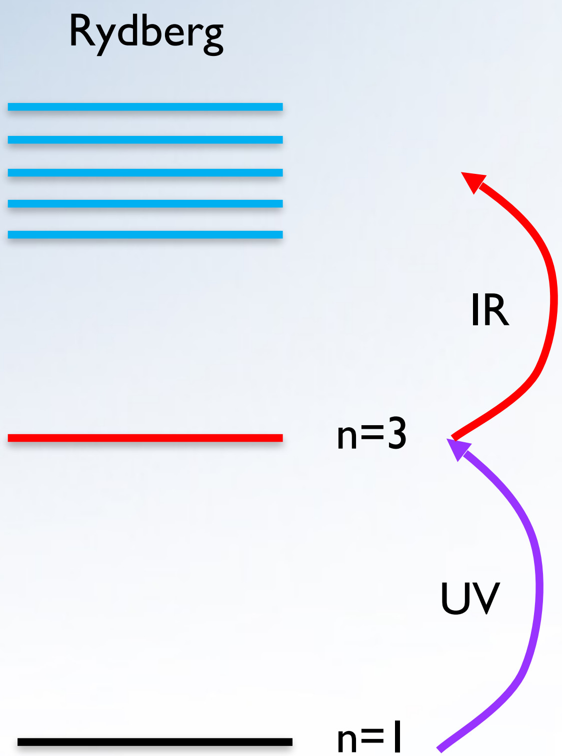


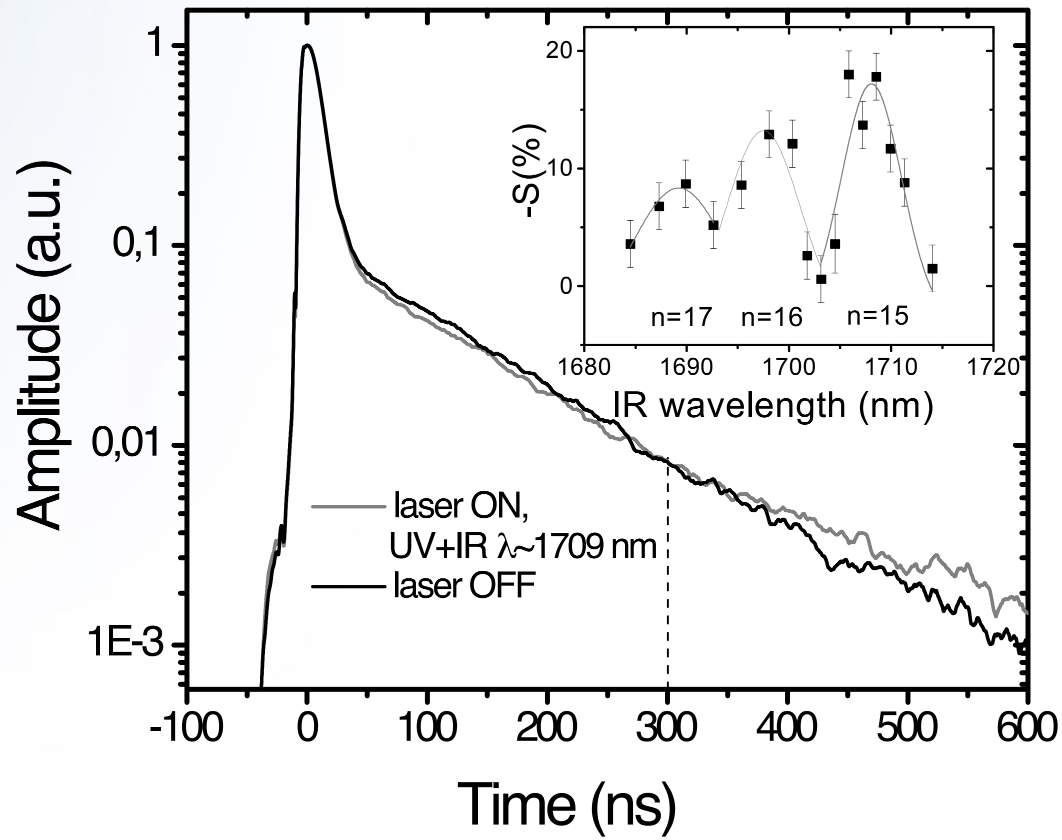






Rydberg excitation

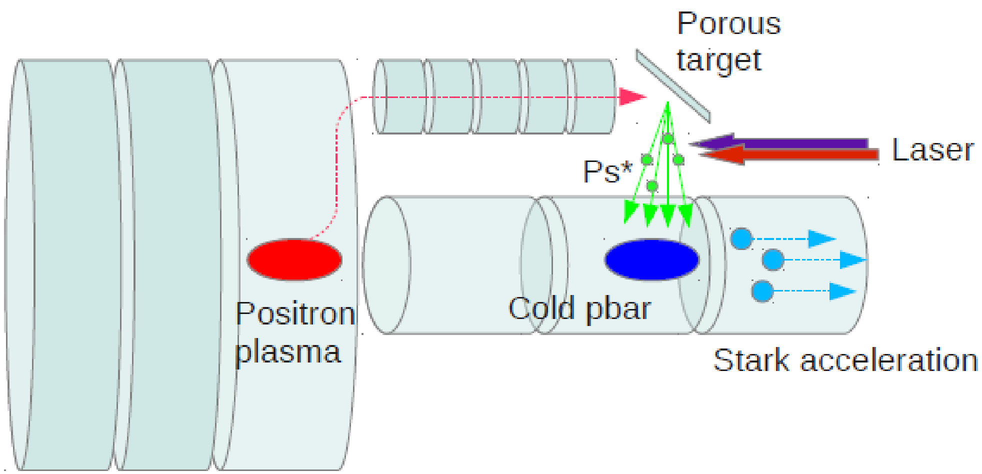


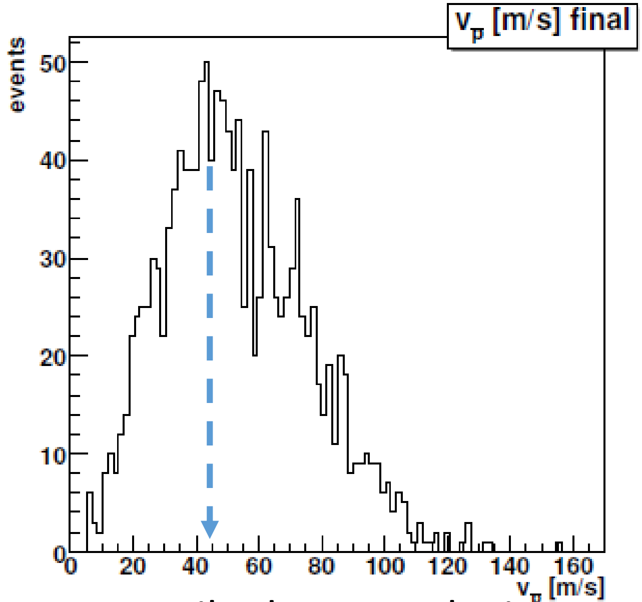


S(%)=(Area laser OFF-Area laser ON)/Area laser OFF

Hbar atoms Production

- Charge exchange reaction: $\bar{p} + (Ps)^* \rightarrow \bar{H}^* + e^-$

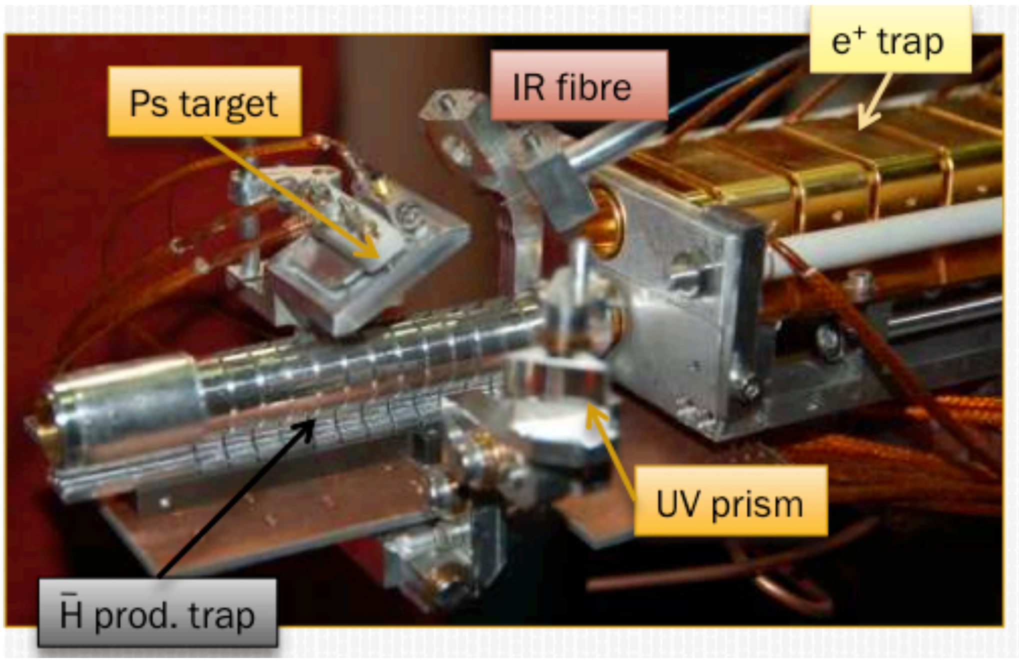




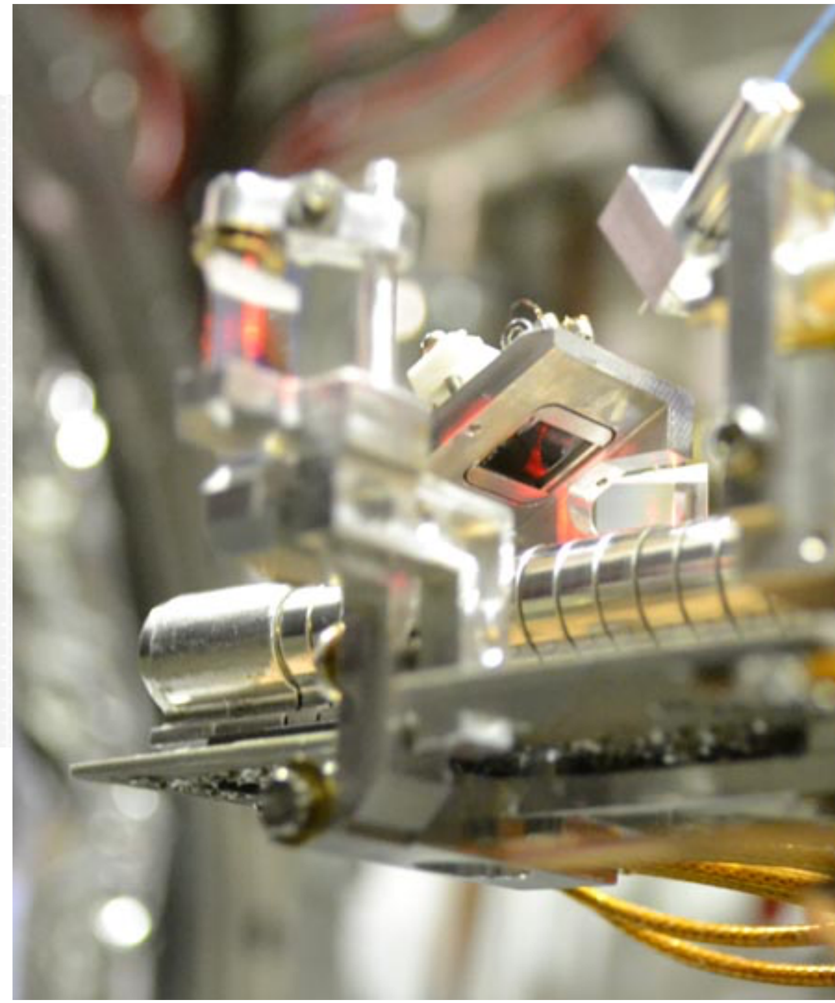
Antihydrogen velocity

  - large xsection: $a_0 n^4$
  - V(Hbar)=45m/s @T=100nK, n=30

Production zone



In the 1T region

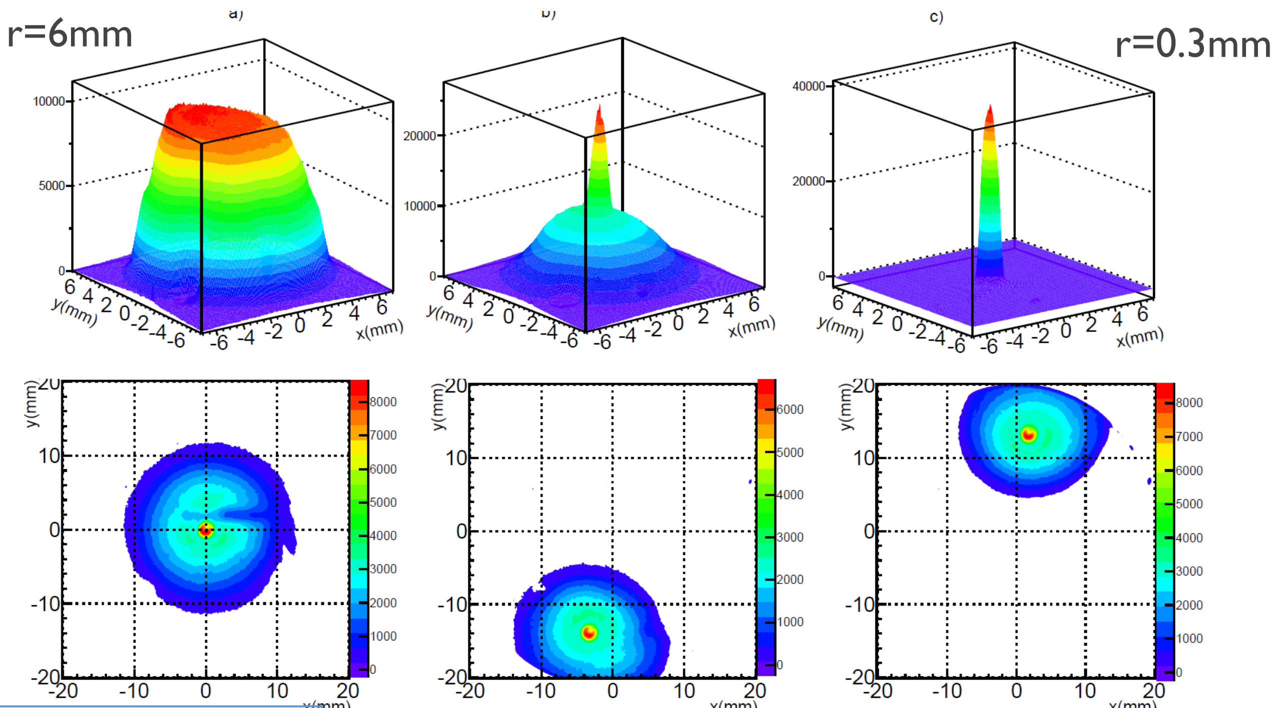


G. Consolati et al., Chem. Soc. Rev. 42, 3821 (2013)

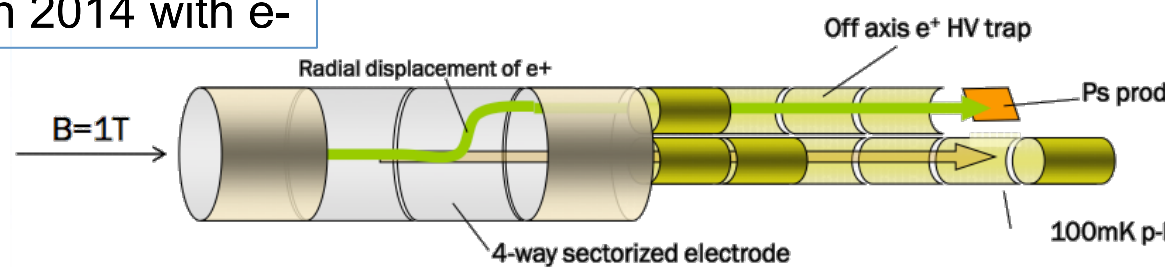
Plasma manipulations in traps

rotating wall

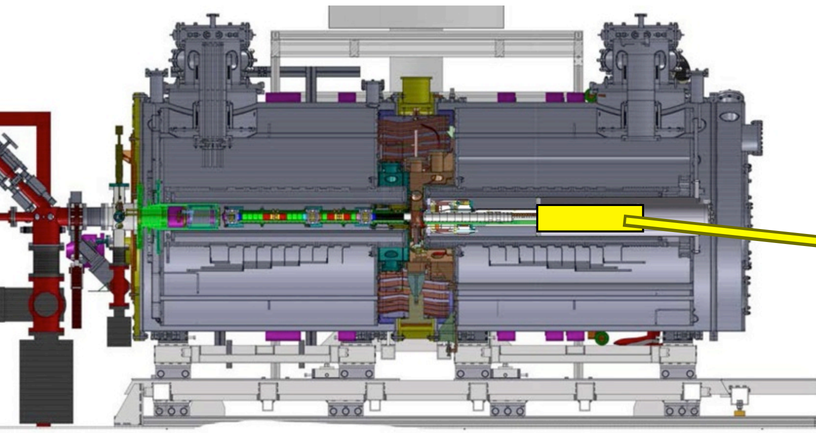
diocotron excitation

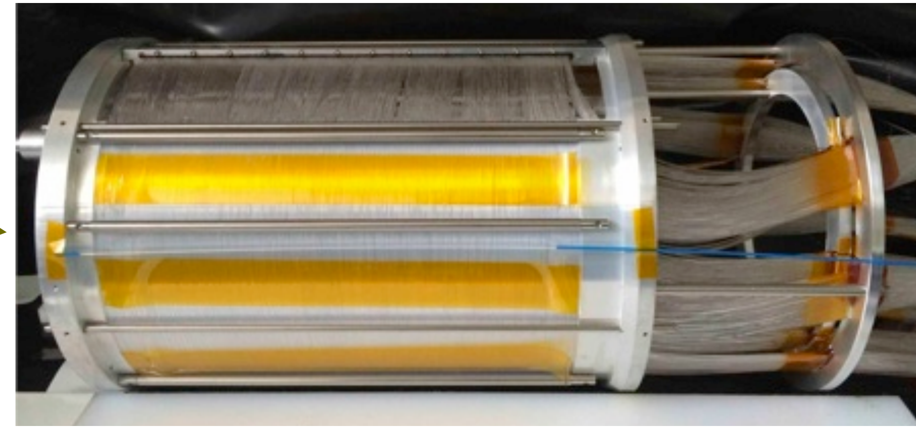


Tests performed in 2014 with e-

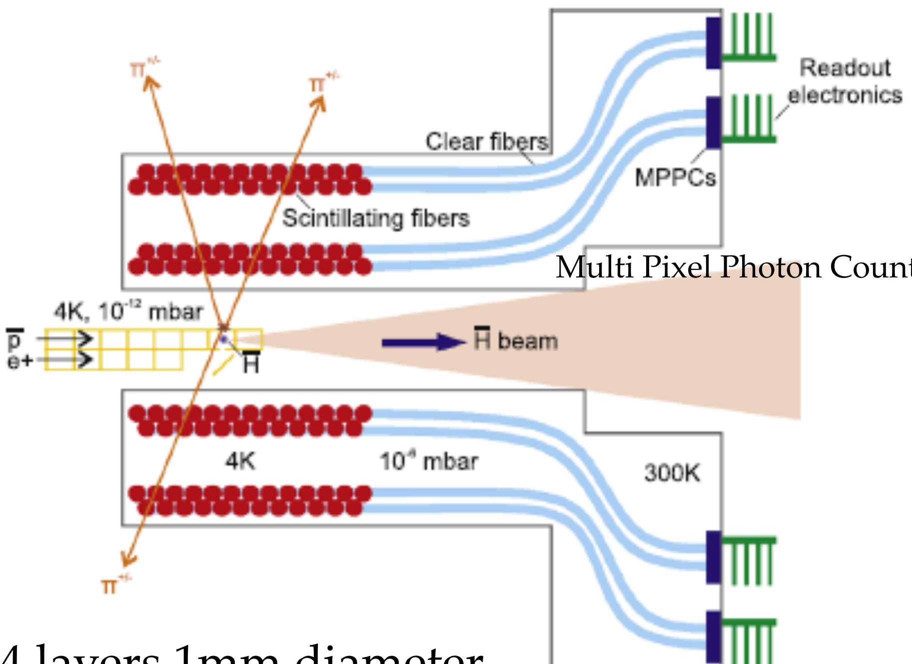


Anti-H monitoring





400 scintillating fibers



Multi Pixel Photon Counters

4 layers 1mm diameter

Nucl Instr. Meth A 732 (2013) 437

Constraints:

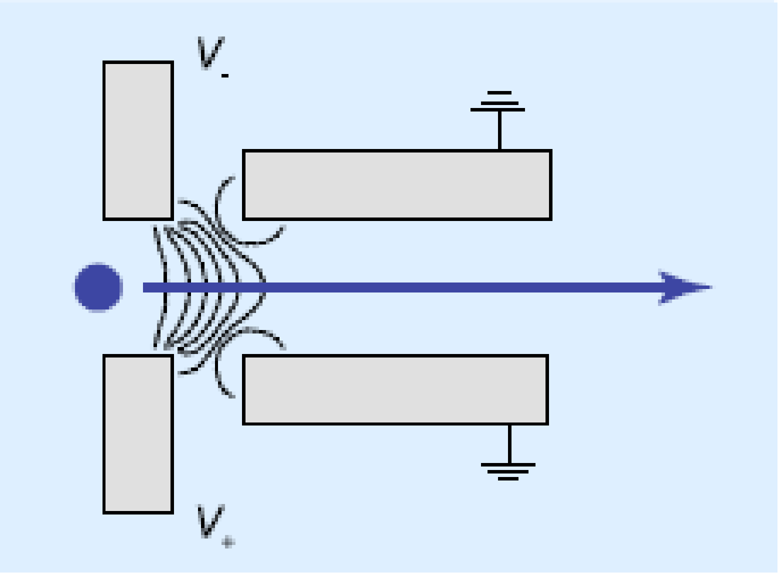
- operate at 4 K, in high vacuum
- inside 1 T
- power dissipation < 10 W.

Fast Annihilation Particle Tracking
resolution ~ 2 mm

Tests with cosmic rays → almost no degradation

Hbar beam

- Accelerate an electric dipole (H*) by an electric field gradient
  - Hbar bea along z axis @ 100 m/s
- Demonstrated with hydrogen



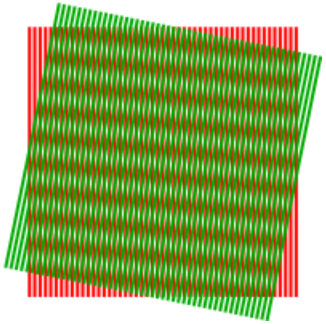
$$\vec{F} = -\frac{3}{2} e a_0 \, n \, (\mathrm{n}-1) \, \nabla \vec{E}$$

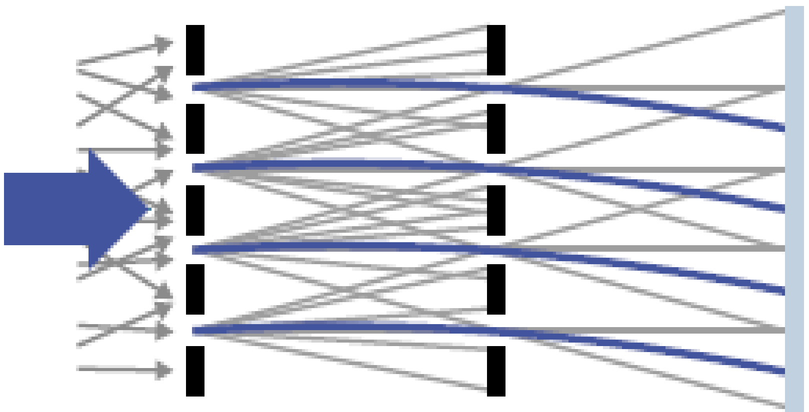
- n = 22, 23, 24
- Acceleration up to 2 x 10^8 m/s^2 achieved

E. Vliegen and F. Merkt, J. Phys. B. 39 (2006) L241.

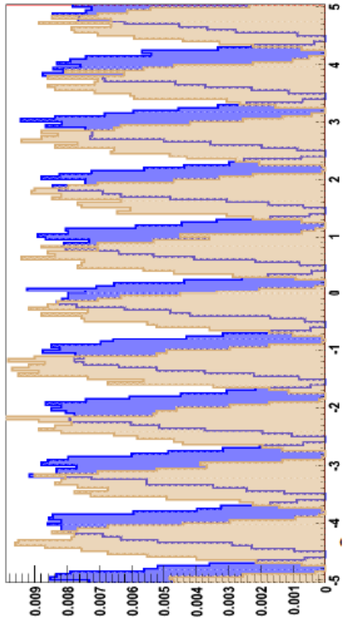
Gravity measurement

- Using a moiré deflectometer + position sensitive detector
- Detection a periodic shift (due to gravity)



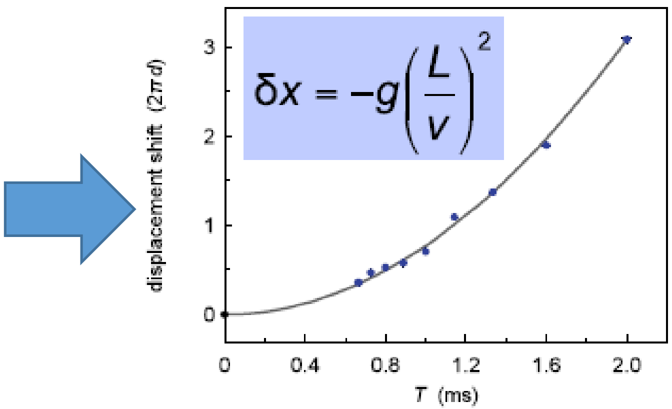


Moirè deflectometer + position detector



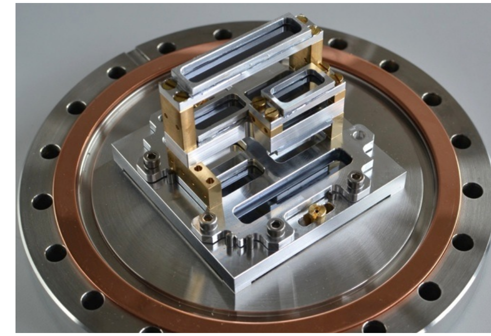
$V_{horizontal}$ = 600 m/s

$V_{horizontal}$ = 250 m/s



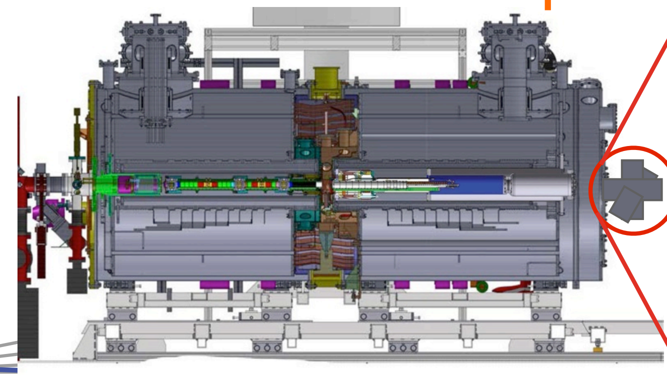
M. K. Oberthaler et al., Phys. Rev. A 54(1996)3165

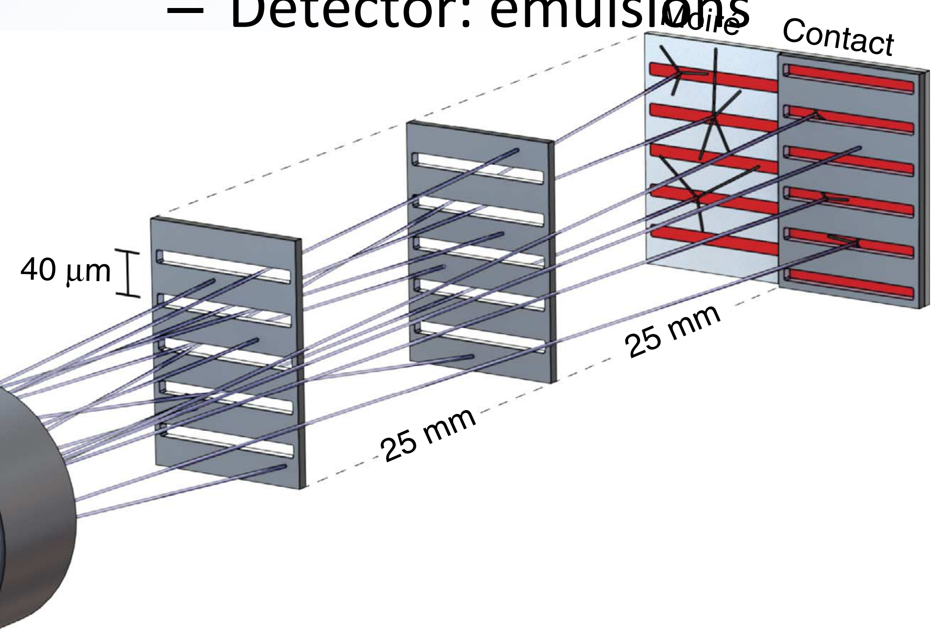
Moiré deflectometer

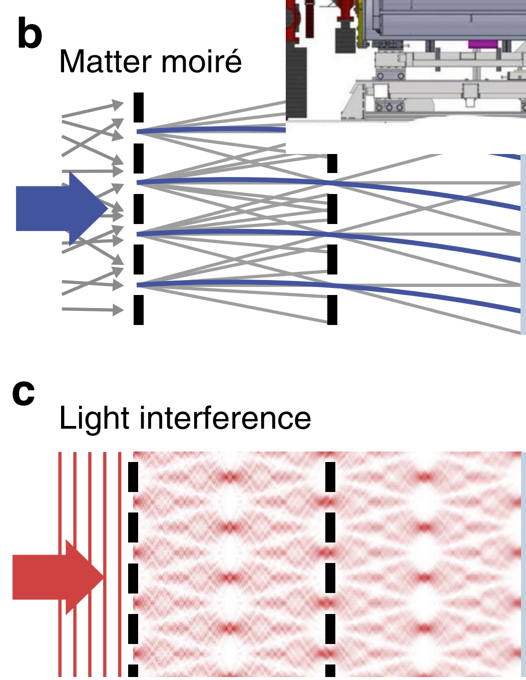


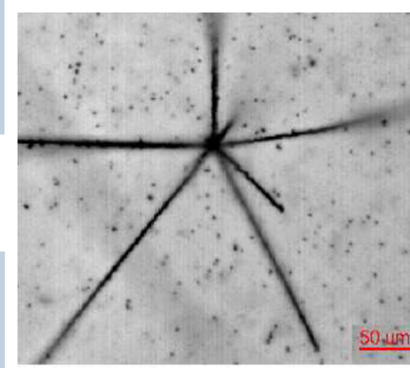
- Proof of principle tested with pbar
  - D=25 mm, pitch=40um
  - Beam (pbar) 100-150 keV
  - Laser beam – reference
  - Detector: emulsions

2012 setup





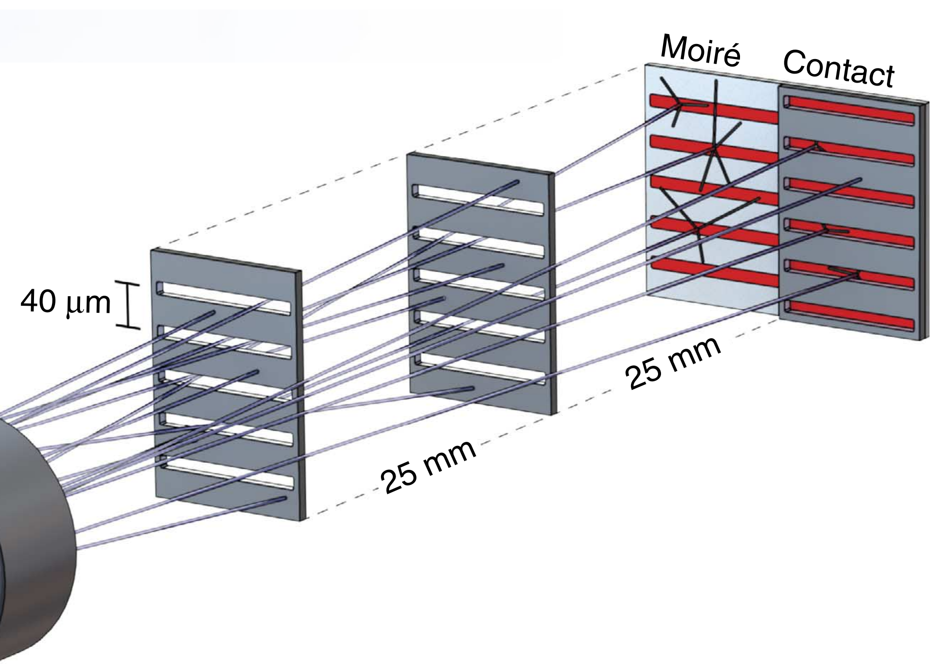


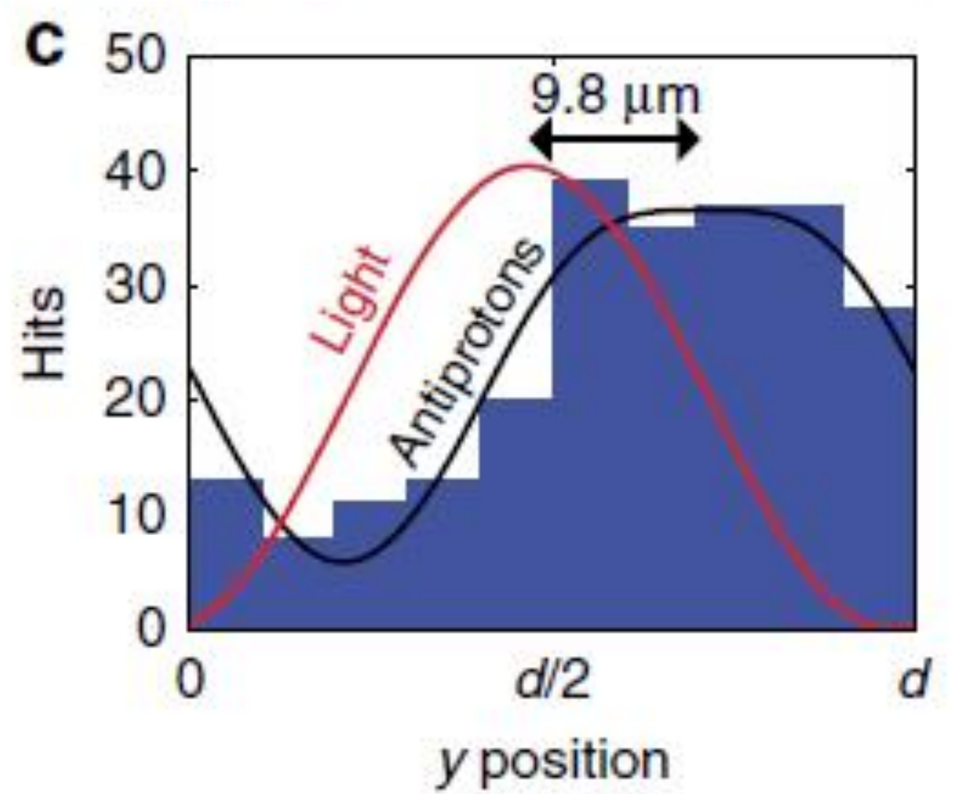


Aghion, S. et al. Nature Communications, 5, 4538 (2014)

Moiré deflectometer

- First demonstration of a moiré deflectometer technique with pbar
  - Displacement ~ 9.8 um
  - F ~ 530 aN (B_{eq} ~ 10 G)



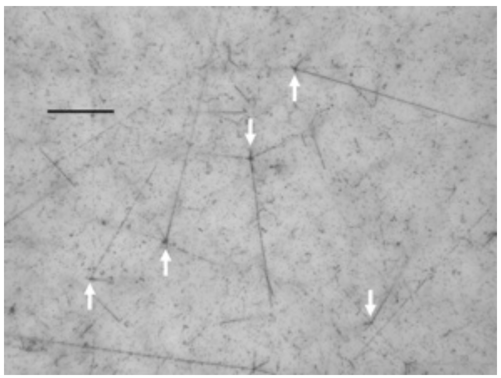


Aghion, S. et al. Nature Communications, 5, 4538 (2014)

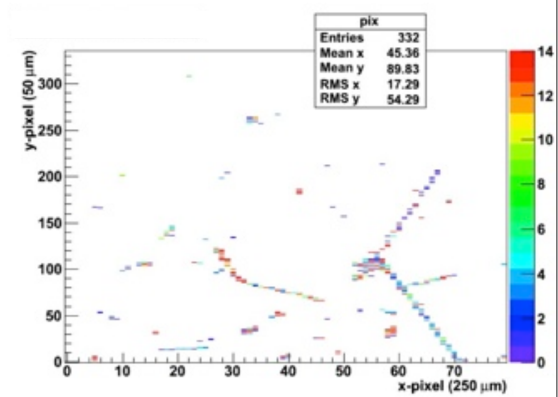
Detection

- We have tested (2012/2014)

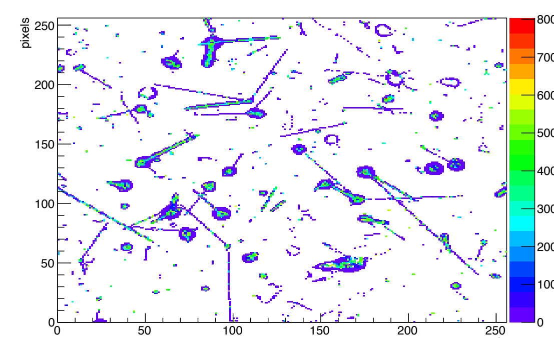
emulsions



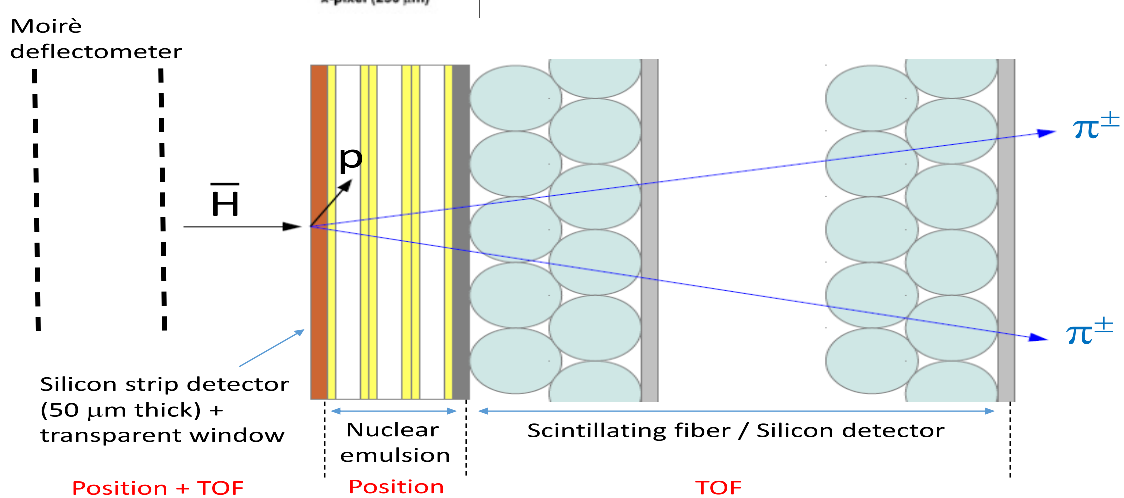
Silicon detector



Timepix3



- Prepare hybrid (emulsion+Si) detector



AEGIS - current status

Achieved so far:

- **Antiprotons** (compression and fast transfer in 1 Tesla) + electron manipulation
- Positron transfer
- oPs, n=1; n=3; n>15 (Rydberg)
- H acceleration (Stark)
- Silicon sensor and emulsion detector tests
- Moiré deflectrometer and time resolution tests

To be done (in situ): 2015/16

- The first goal is to produce pulsed antihydrogen formation at 4 K
- Ps* spectroscopy

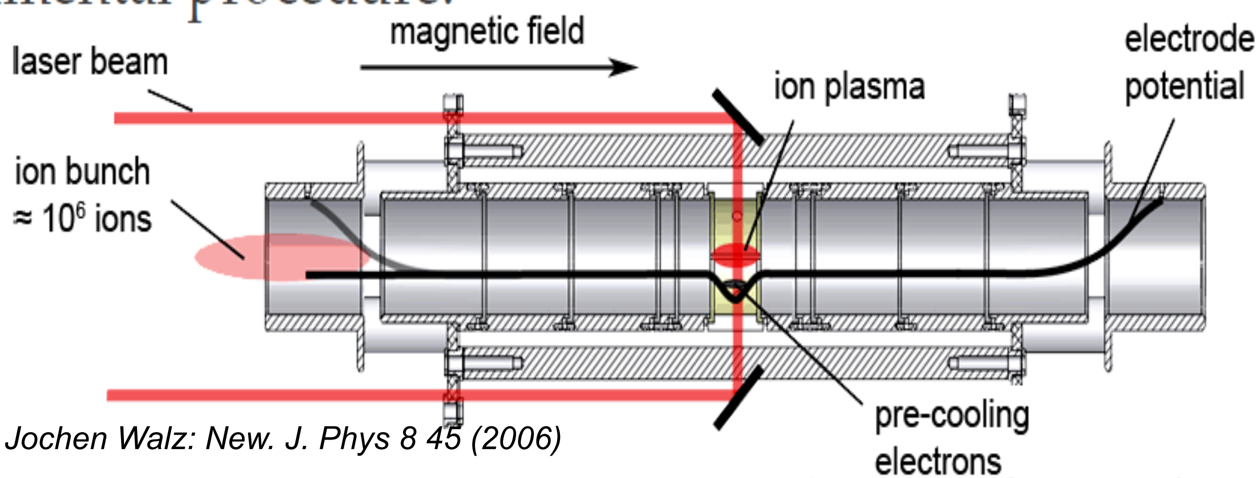
Further improvements (in situ & test labs): 2016/2017

- Ps formation, anti-H beam formation,
- Gravity setup – **First measurement**
- Increase e+ (new source)
- Improve pbar cooling (C_2^- cooling)
- New pbar beam (ELENA)

Colder pbar

- Cold pbar to maximize flux
  - T~100 mK (7K now)
- Sympathetic laser cooling with negative ions

Experimental procedure:

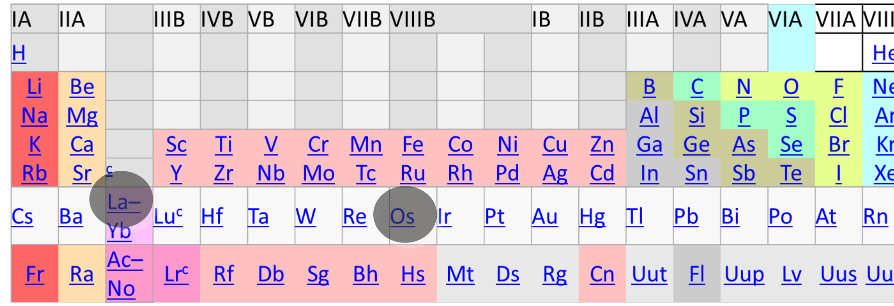


Alban Kellerbauer & Jochen Walz: New. J. Phys 8 45 (2006)

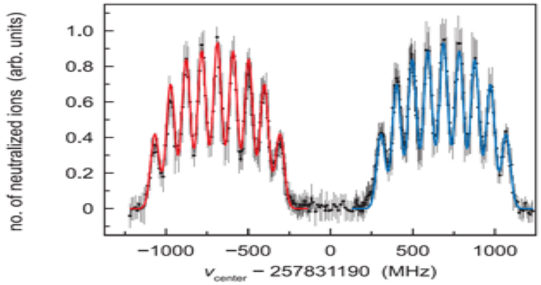
1. Capture of anions in the Penning trap
2. Pre-cooling of anions with electrons
3. Laser cooling of anions
4. Simultaneous confinement of antiprotons in the trap
5. Sympathetic cooling of antiprotons by anions

Atomic anions ?

One bound state lying below the neutral



Os^-



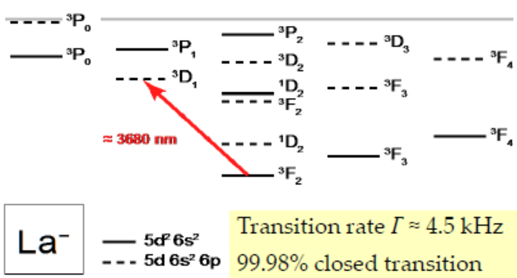
*A. Kellerbauer et al., PRA **89** (2014) 043430*

Max-Planck Institute Heidelberg

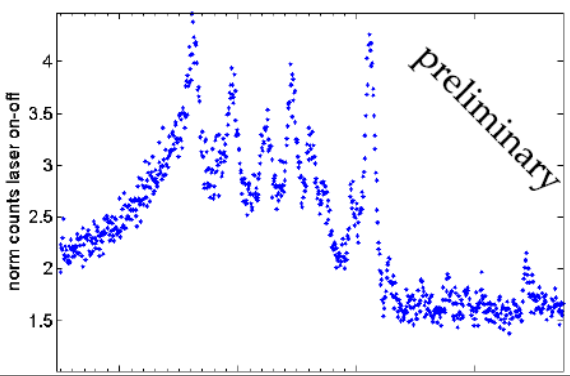
Max-Planck-Institut für Kernphysik

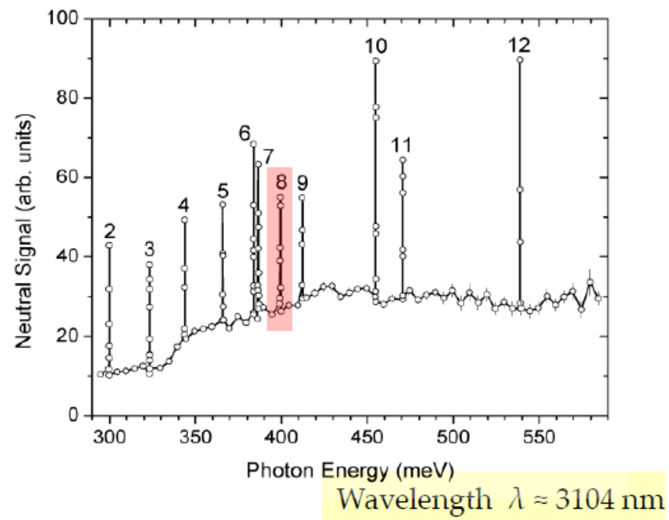
Kellerbauer Alban

La^-



- First La⁻ resonance recorded at MPIK:





[S. M. O'Malley & D. R. Beck, Phys. Rev. A 81 (2010) 032503]

[C. W. Walter *et al.*, Phys. Rev. Lett. 113 (2014) 063001]

Difficult to produce + Low cooling rate + spectroscopy unknown +photodetachement

University of Paris Sud
Comparat Daniel

Why not molecules!

CERN
Doser Michael

2010: DeMille's group demonstrates laser collimation with a radiative force on SrF
2014: Show 3D cooling and trapping: Nature 512, 286–289 (21 August 2014)

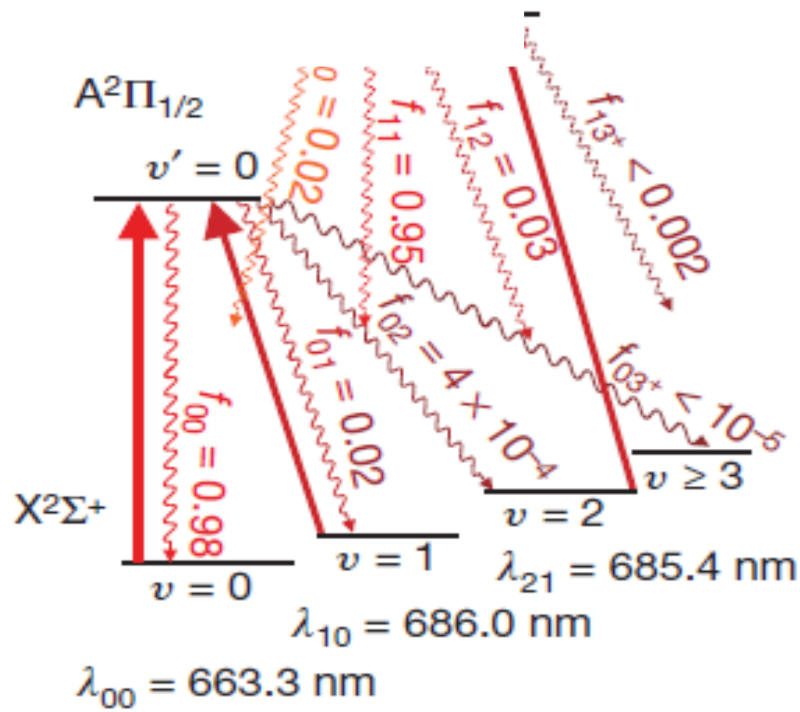
LETTER

doi:10.1038/nature09443

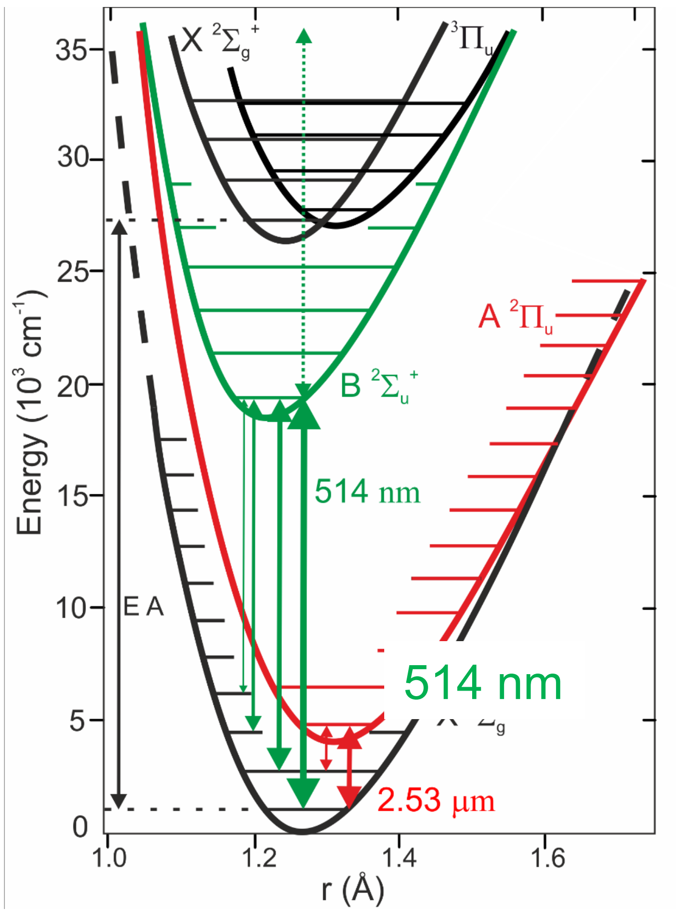
Laser cooling of a diatomic molecule

E. S. Shuman[1], J. F. Barry[1] & D. DeMille[1]

Like a 2 level atom: 98% of branching ratio



Example (best known molecule) C_2^-



10 lasers

10 K → 100mK in 100 ms

30% losses (photodetachment)

2 possible cooling schemes

- $X\,^2S_g^+ \rightarrow B\,^2S_u^+$

541, 598, 667, 753 nm

probability (Franck-Condon) 72, 23, 3, 0.8

Ultra fast cooling : lifetime 70ns

high photodetachement s ~ 10^{-17} cm^2

→ rate I s/h n=1/s for I = 30mW/cm^2

- $X\,^2S_g^+ \rightarrow A\,^2P_u$

2.53 µm and 4.50 µm

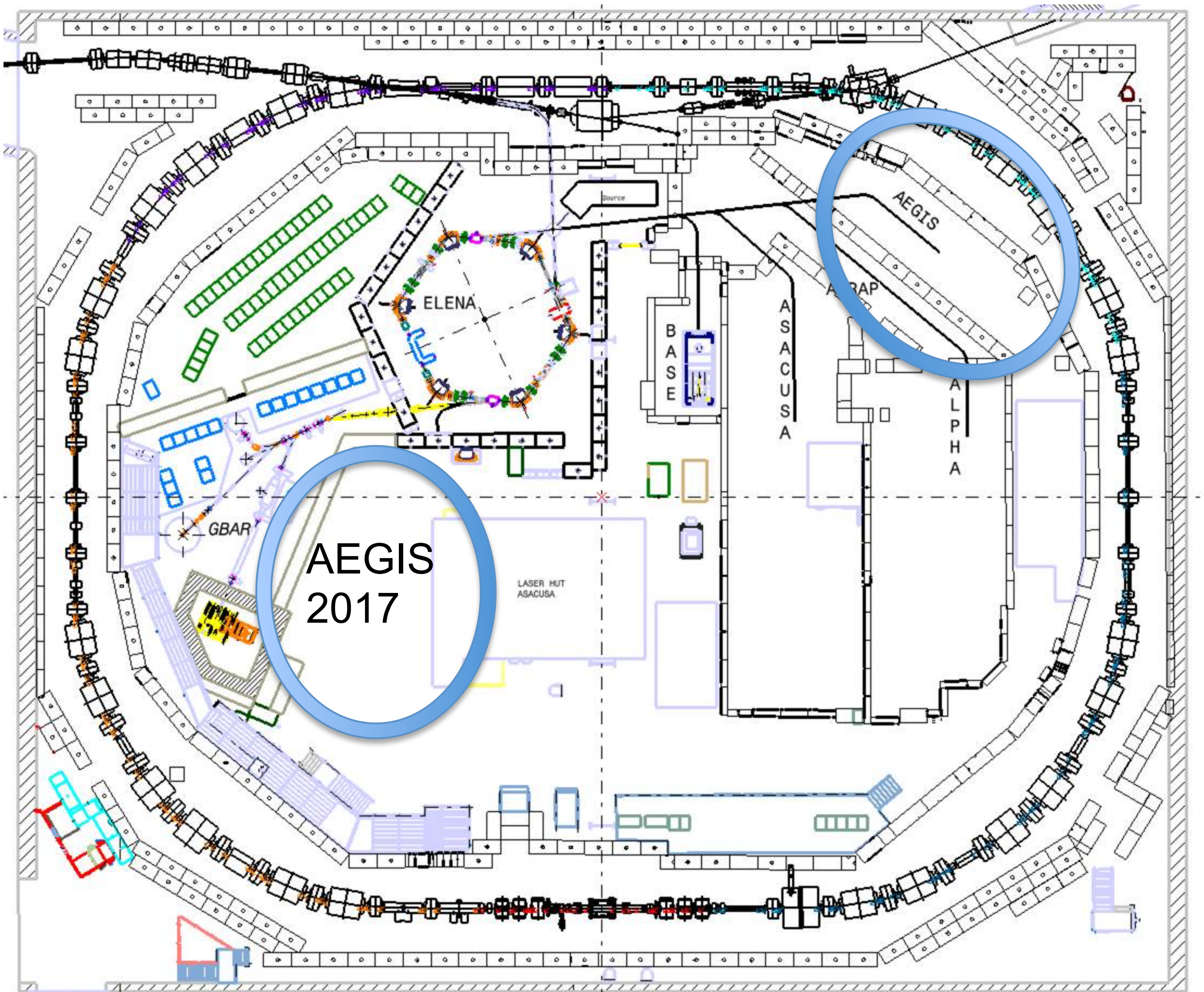
Less laser needed

slower cooling (100µs)

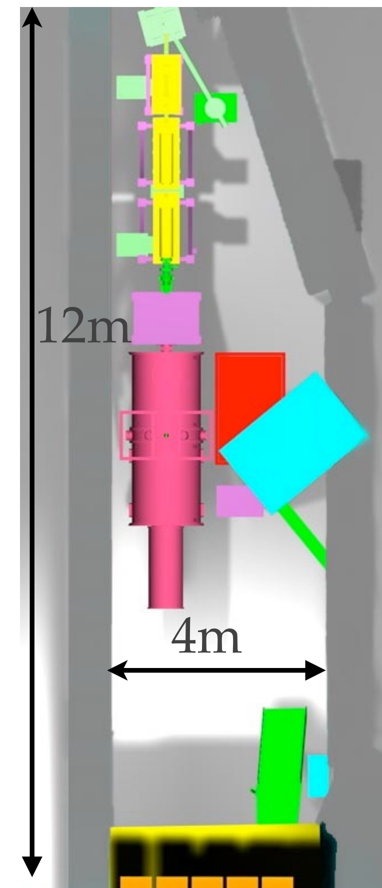
No photodetachement

Easy to produce + Fast cooling rate + spectroscopy known + no-photodetachement

Extremely Low Energy Antiproton area



Pbar 100 keV
En //



Matter wave interferometer and deflectometer

$$\delta\varphi_{\text{beam}} < \varphi_{\text{diffr}} = \lambda_{\text{dB}} / d$$

v = 1000 m/s
d = 0.1 μm
$\partial\varphi_{\text{beam}}$ < 4 mrad
T < 1 mK

where d – grating period
v – beam velocity

Currently not feasible

– diffraction requirement on angular beam divergence:

Mach–Zehnder interferometer:

$$\lambda_{\text{dB}} > d^2/L$$ (far-field diffraction)

Talbot–Laue interferometer:

$$\lambda_{\text{dB}} = d^2/L$$ (near-field diffraction)

Moiré deflectometer:

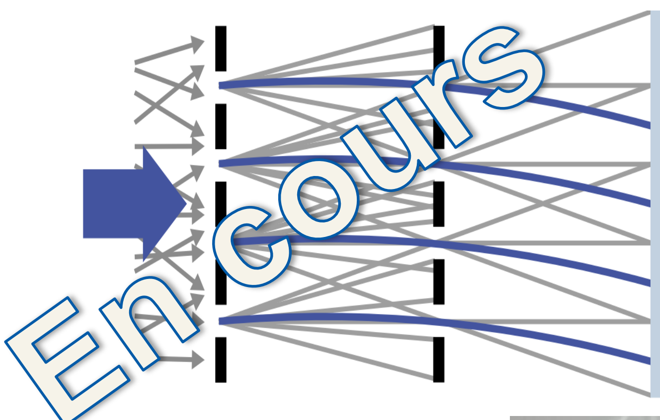
$$\lambda_{\text{dB}} << d^2/L$$ (no diffraction)

AEGIS

Interferences quantiques

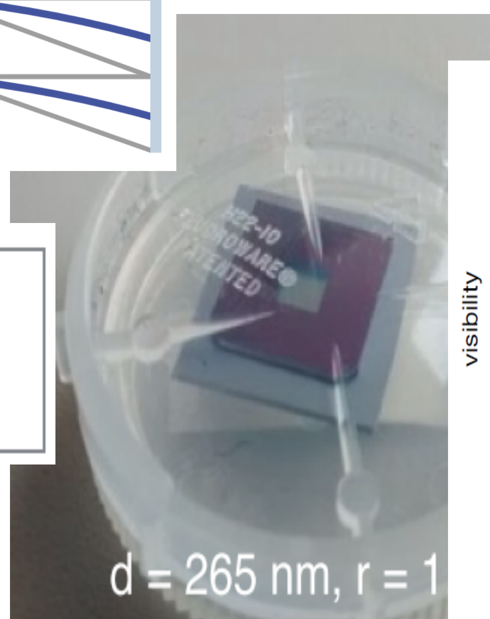
Proton interferometry – outlook

classic regime



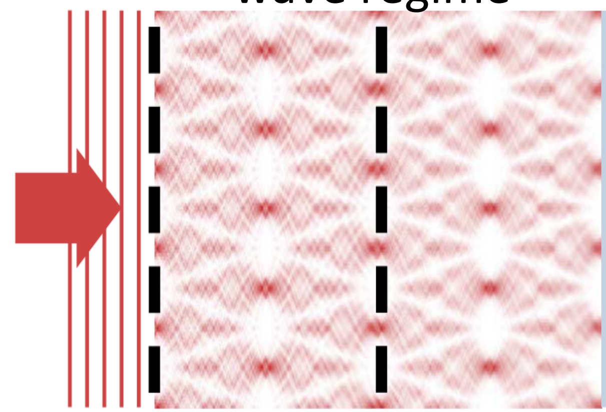
Talbot-length:

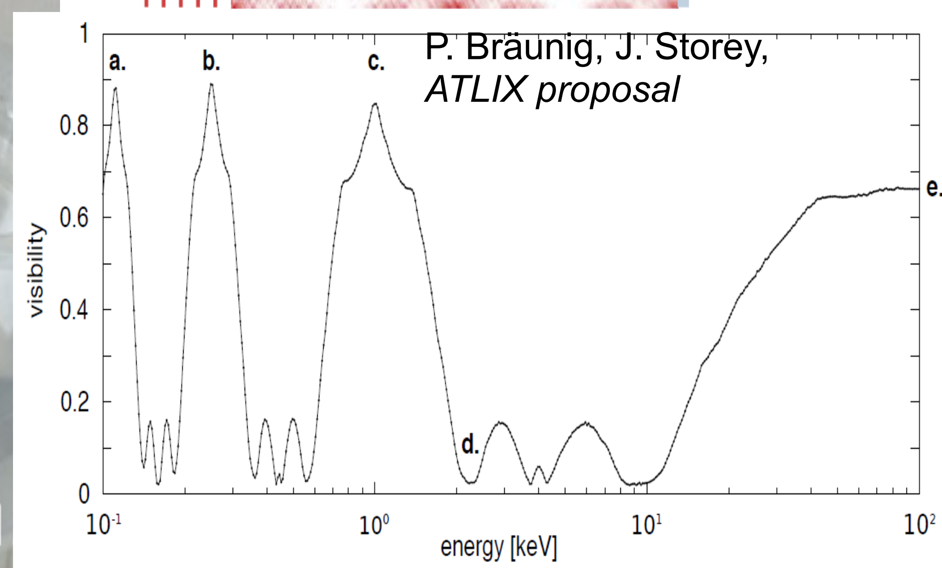
$$L_{\mathrm{T}} = \frac{d^2}{\lambda}$$



visibility is the signal!

wave regime





Merci