H·HFS
Hyperfine Structure of Antihydrogen

ERC Advanced Grant
PI: Prof. Dr. Eberhard Widmann

Antimatter gravity measurement in a beam - the AEg IS experiment

E. Widmann
Stefan Meyer Institute for Subatomic Physics, Vienna
on behalf of the AEg IS collaboration

INPC2016
Adelaide, Australia
15. Sep. 2016

ÖAW

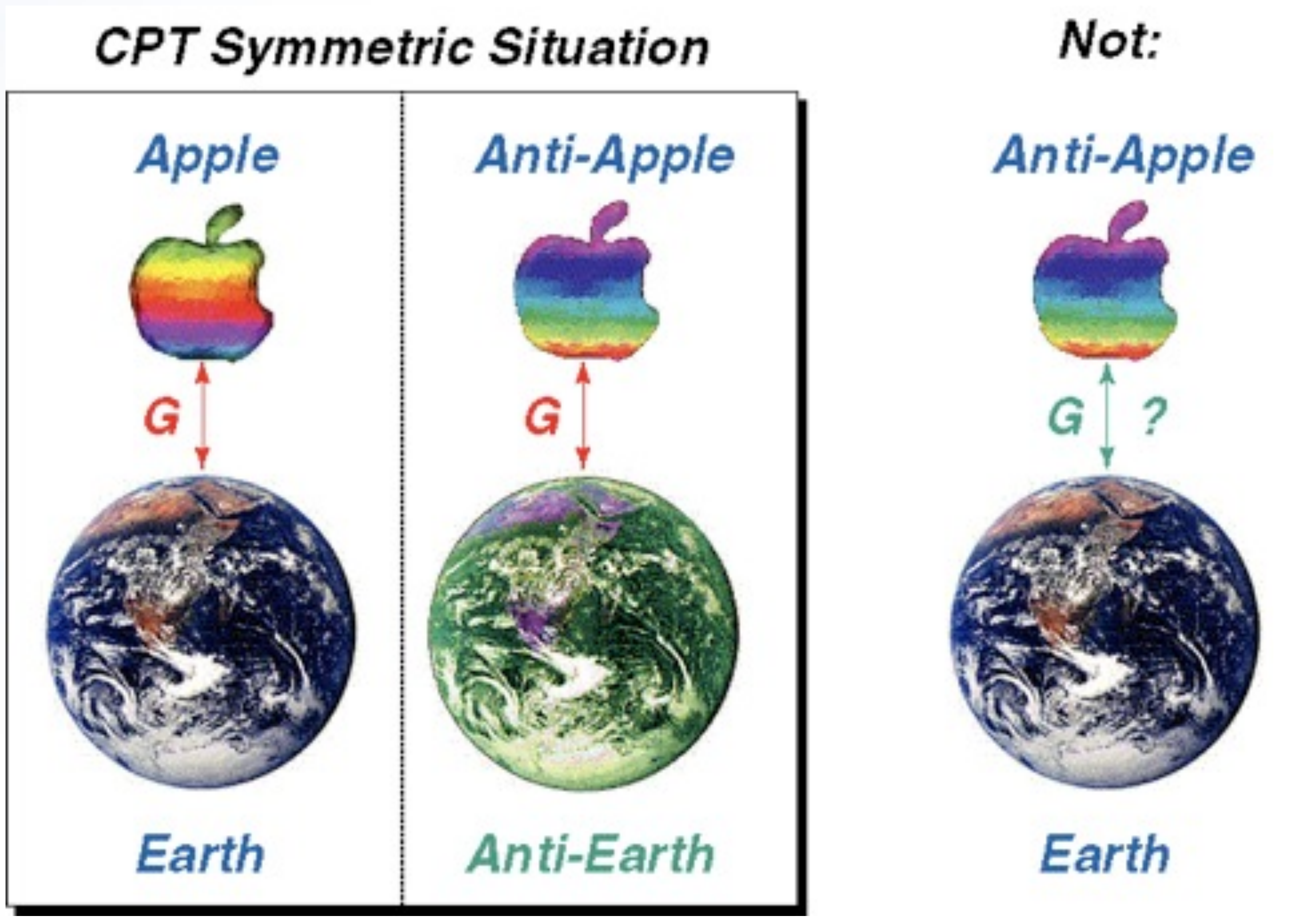
erc

AEgIS collaboration

ÖAW 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			

Gravitational Acceleration of Antimatter

- No direct test of CPT
  - Weak equivalence principle
- no precise experimental test available
- Highest precision reachable with neutral antimatter
- AEg IS
  - Antimatter Experiment - g ravity, Interferometry, Spectroscopy



E. Widmann

Antimatter and gravity

- Antigravity: $g_{matter} = -g_{antimatter}$
  - separation of matter and antimatter in Universe
- Quantumgravity
  - Graviton (S=2)→adds Gravivector (S=1), Graviscalar (S=0)
  - simplest case: static potential

$$V = -G m_1 m_2 / r \, (1 \ldots$$

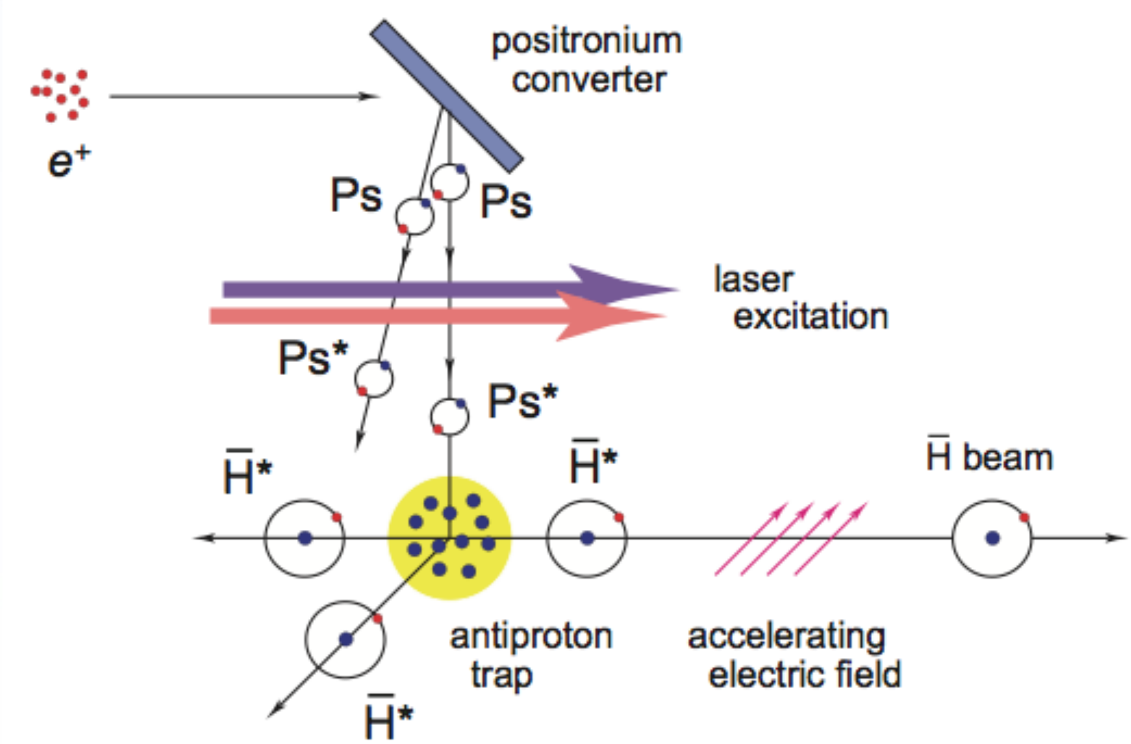
  - a: Gravivector, b: Graviscalar
  - − attractive (matter-matter), +: repulsive: matter-antimatter
  - matter experiments: $|a-b|$
  - antimatter: $a+b$

AEg IS Goal

- First goal is to measure g to $\mathcal{O}$(1-10%)
  - in the free fall of cold H atoms
- Test of WEP on antimatter in the Earth's gravitational field
  - First direct measurement for antimatter - no assumptions
  - Large amount of antimatter atoms needed
- AEg IS method
  - Produce cold Rydberg H^*
  - Accelerate H^* to produce neutral beam
  - Measure gravitational deflection of H beam using a Moiré deflectometer

Production of H atoms

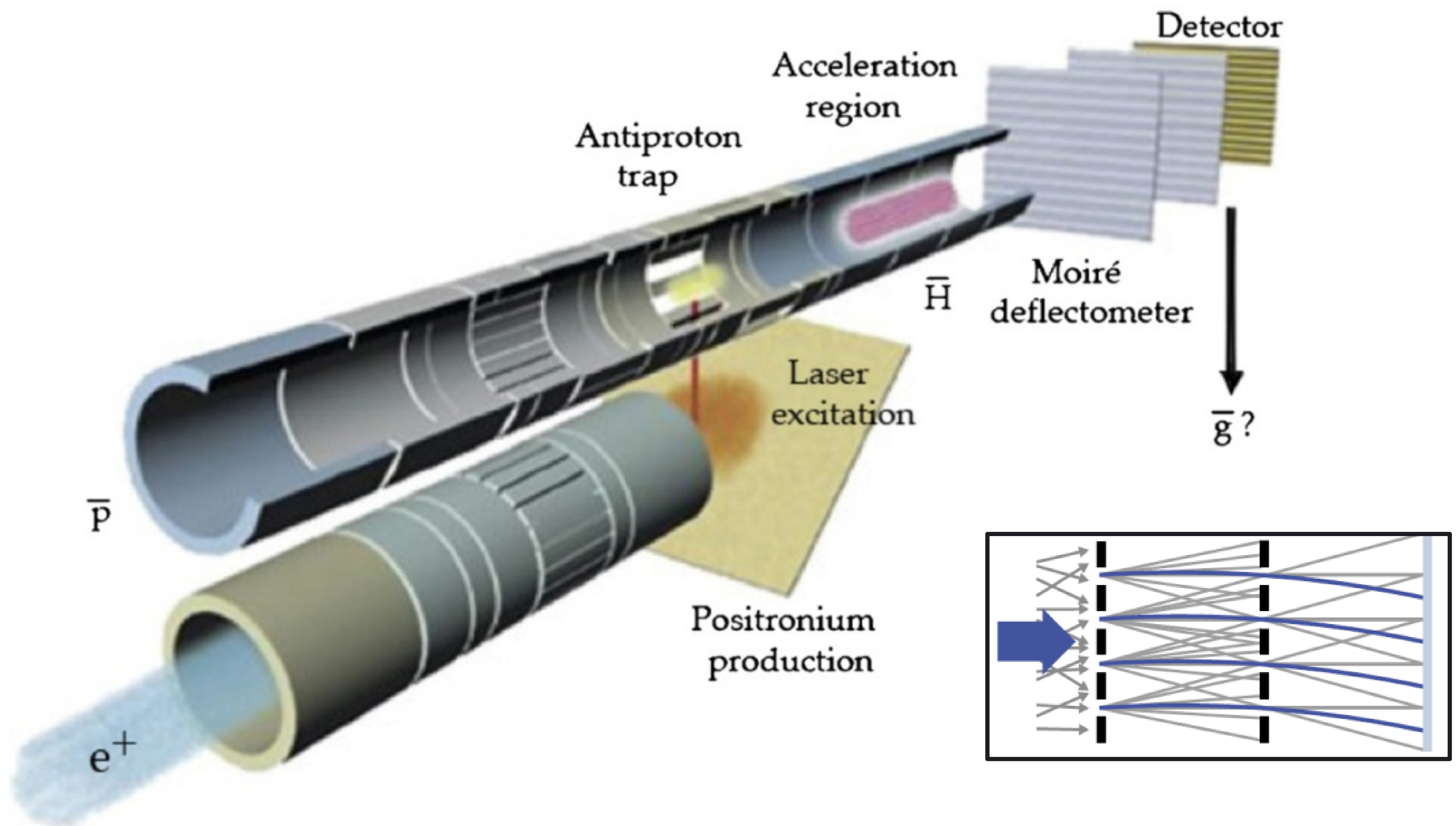
- Charge exchange with Ps*
  - Capture p from CERN-AD
  - Cool p
  - Ps production by e^+ on SiO_2
  - Ps laser excitation to Rydberg state
  - Interaction Ps* with p cloud
  - Recombination: resonant charge exchange



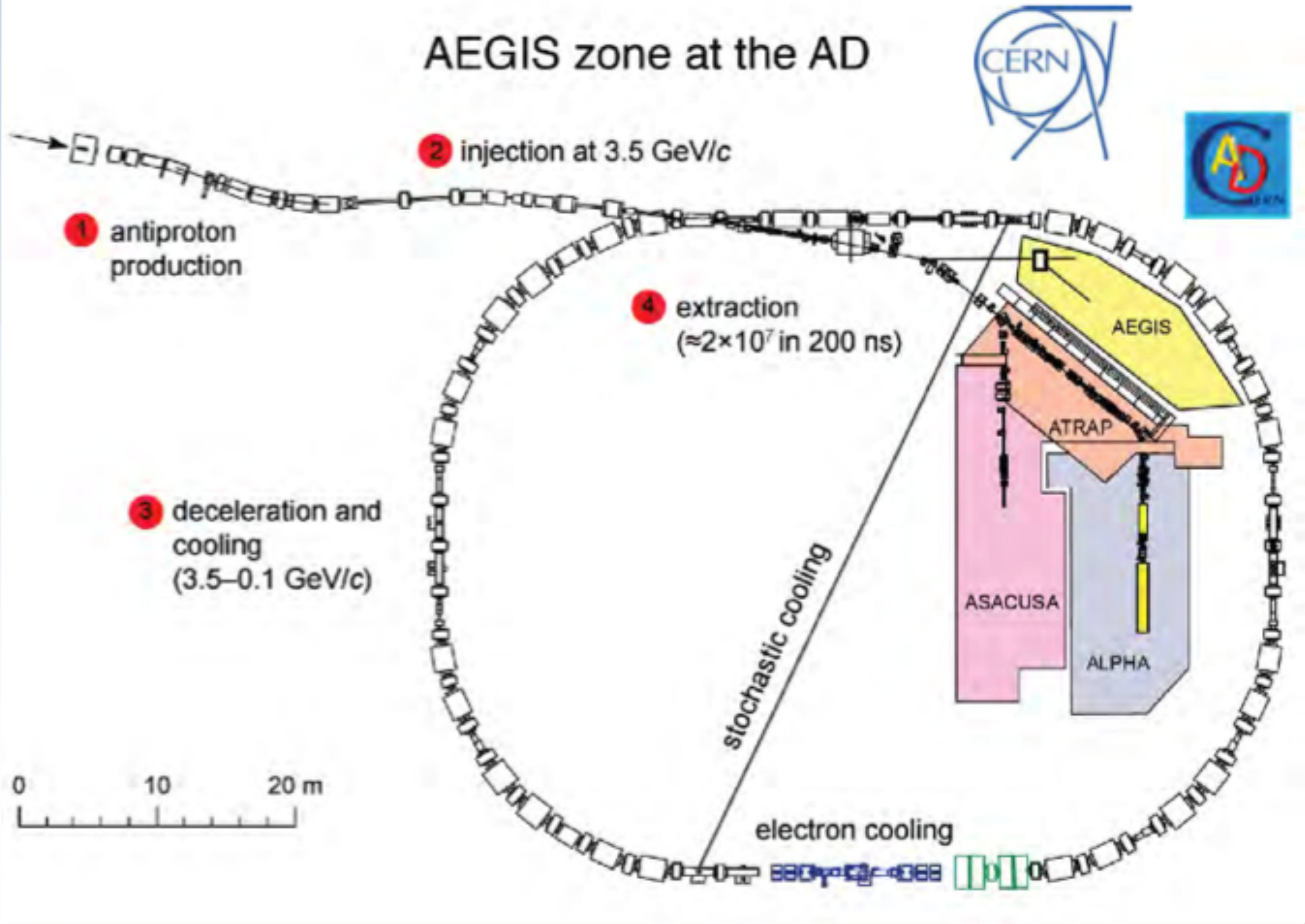
$$Ps^* + p \rightarrow e^+ + H$$

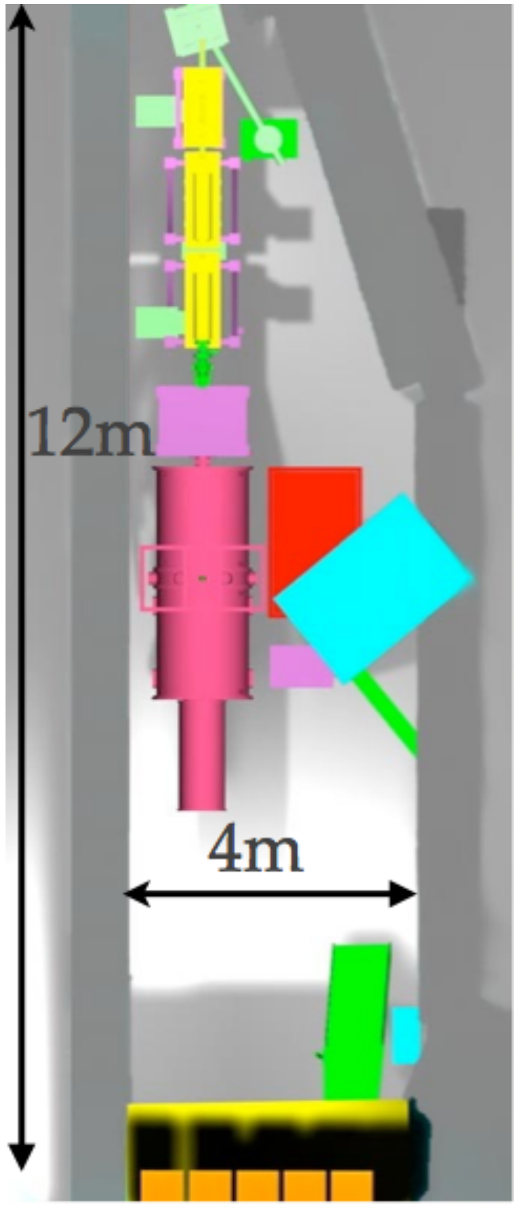
enhanced formation rate:
$\sigma \sim n^4$
$Ps(n_1) \rightarrow \quad (n_2)$

AEg IS principle

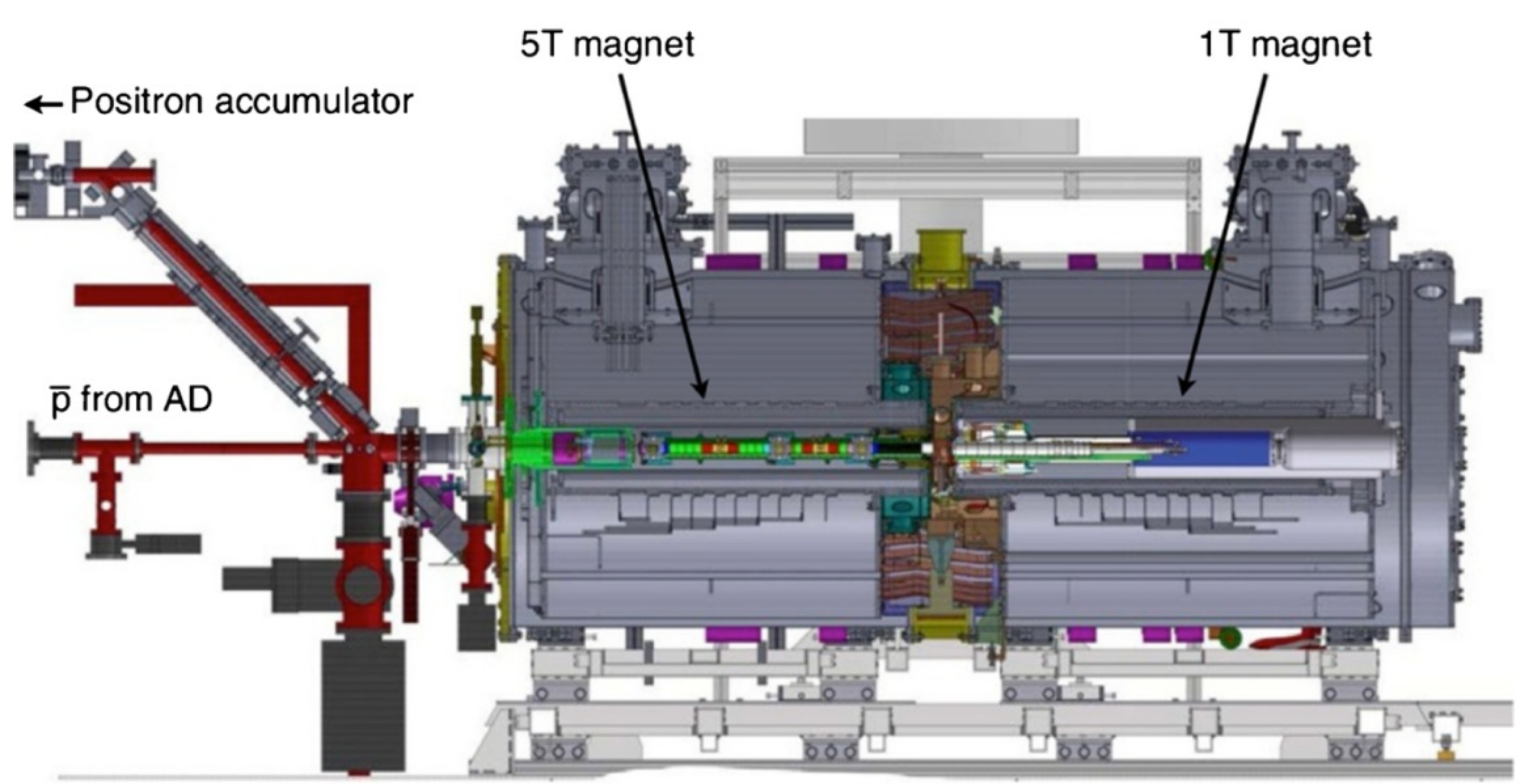


Experimental setup: CERN-AD

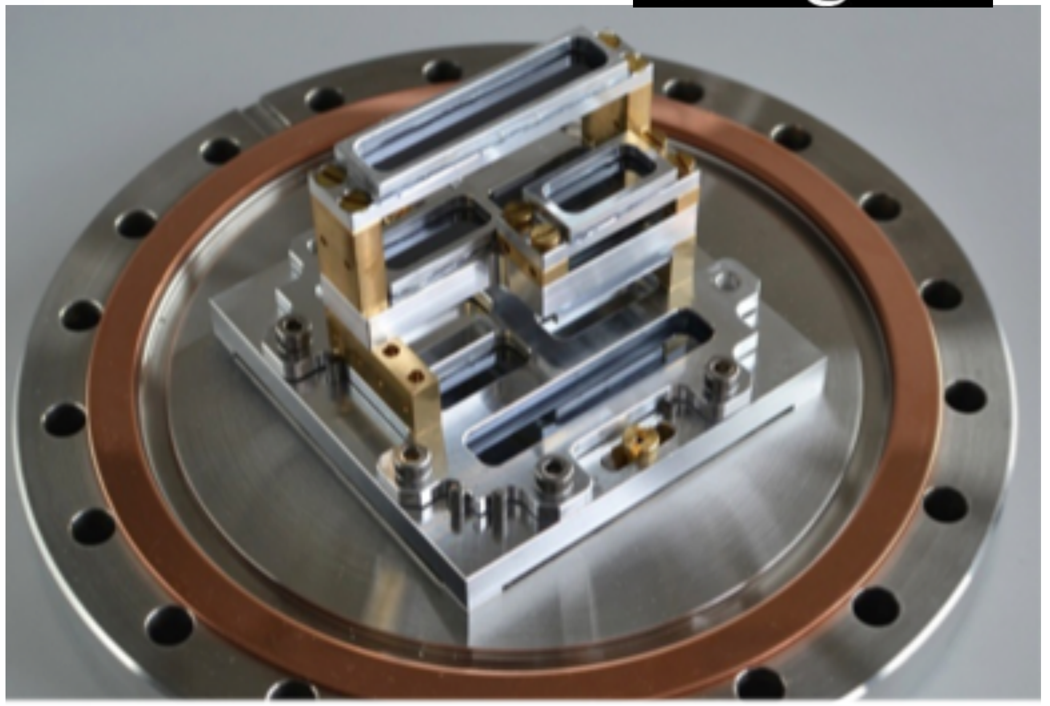




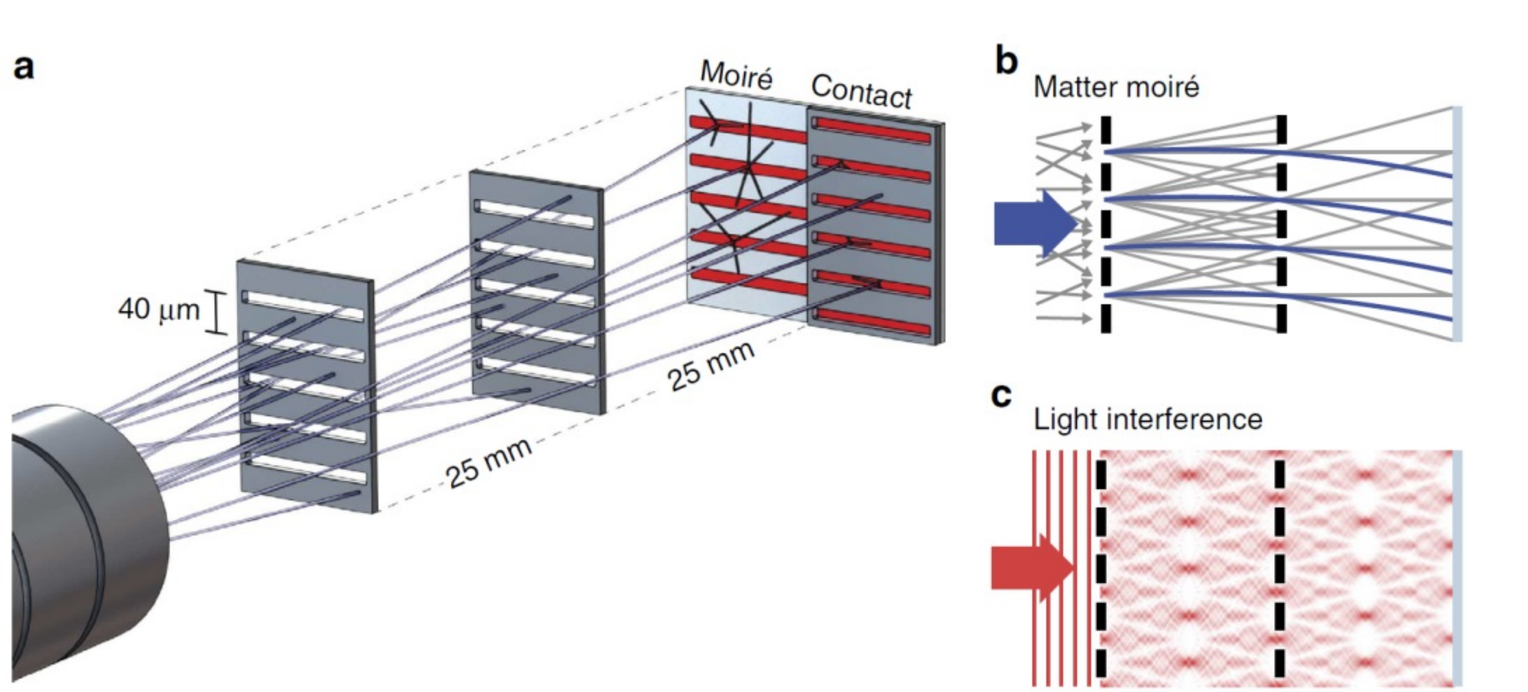
AEgIS Setup



Gravity measurement - proof of principle



- Mini-moiré deflectometer
  - distance 25 mm
  - slit 12 μm, pitch 40 μm, 100 μm thick
  - p beam E~(100±150) keV traversing 1T magnet
  - light reference: Talbot-Lau
  - emulsion detector



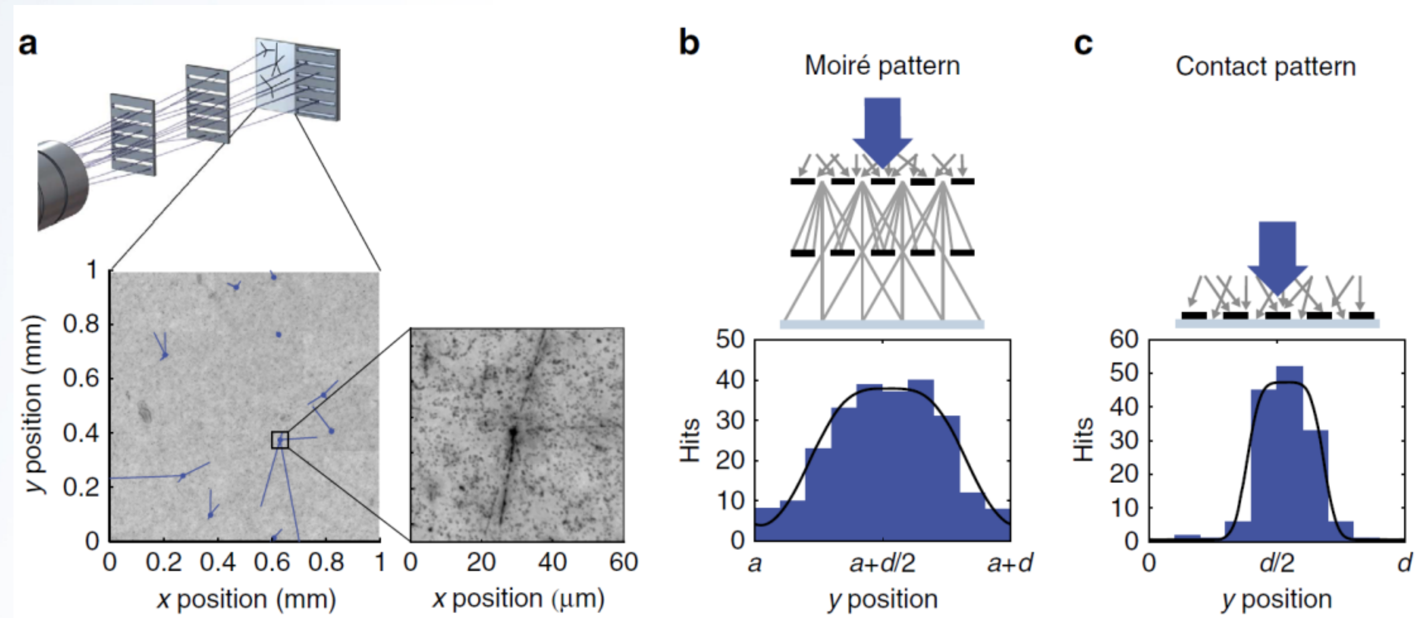
Aghion, S. et al. Nature Communications 5, 4538 (2014)

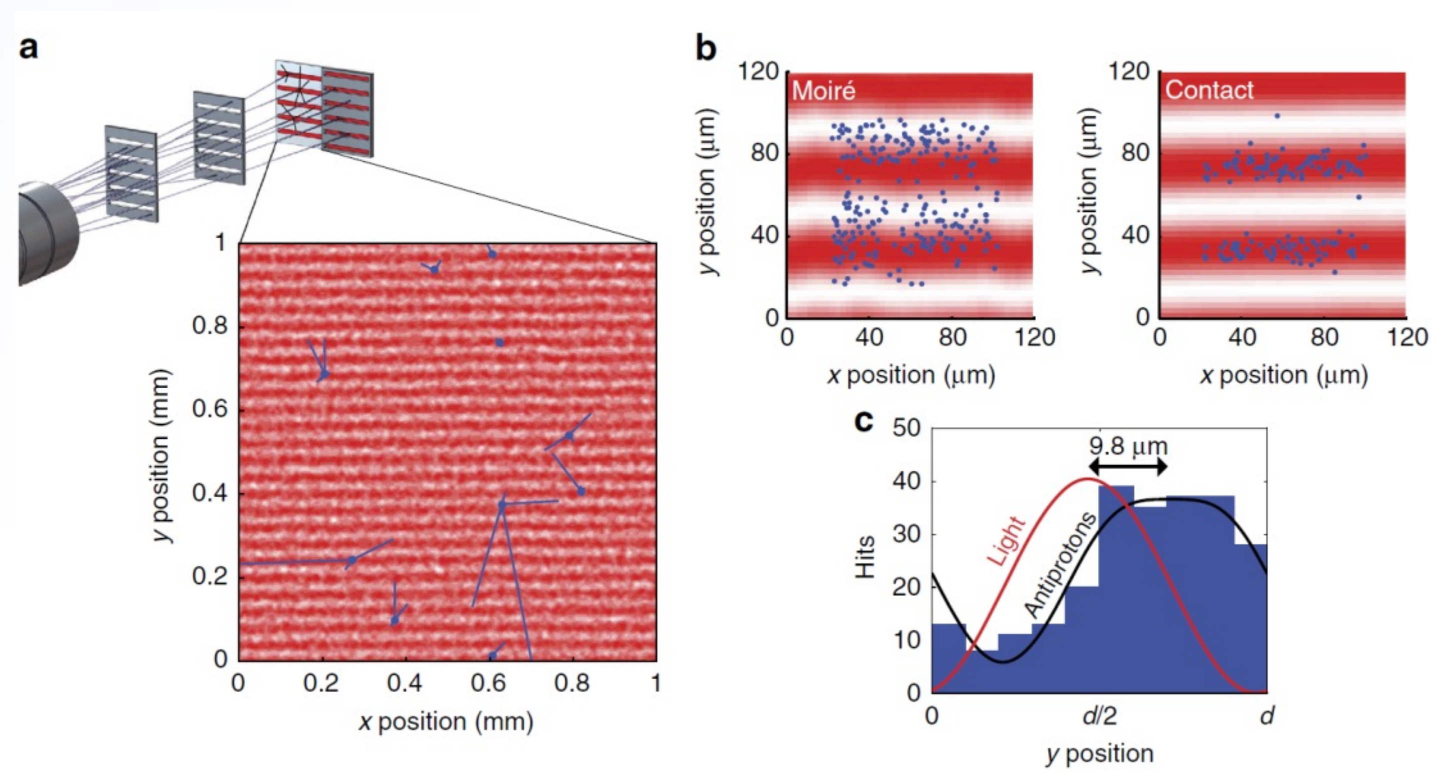
p deflectometer result

- Pattern observed
  - Shift between p and light observed

Δy=9.8±0.9(stat)±6.4(syst)μm

  - consistent with residual B, E fields
  - sensitivity of μm reached
  - H beam case
    - velocity *10^{-4}
    - distance * 40
    - Force 10^{-10}





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

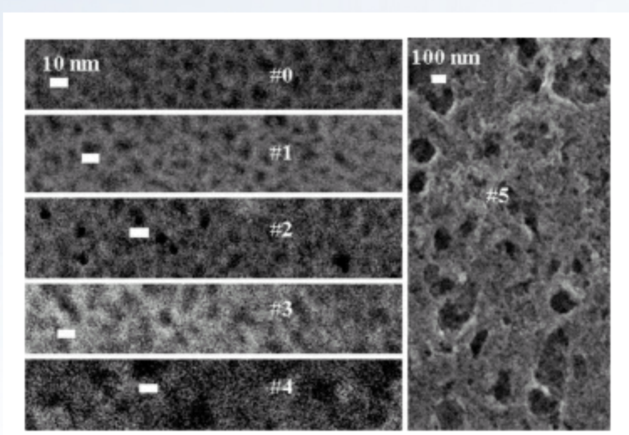
Ps production: SSPALS measurement

Cassidy D B et al., *NIMB* 2007, 580, 1338

~4 x10^6 Ps atoms in vacuum

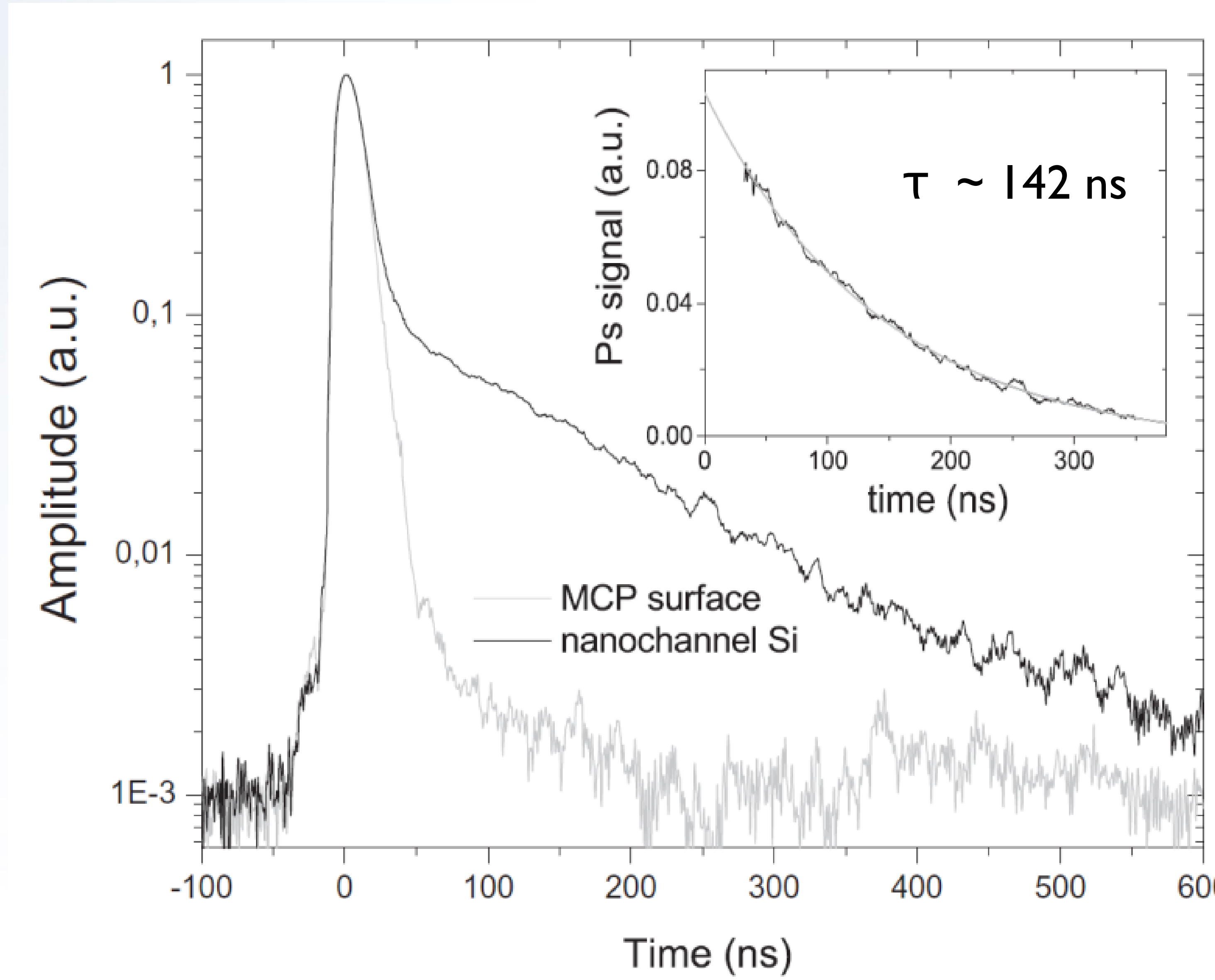
$PbWO_4$ detector

e+/Ps converter



Nanochanneled Si

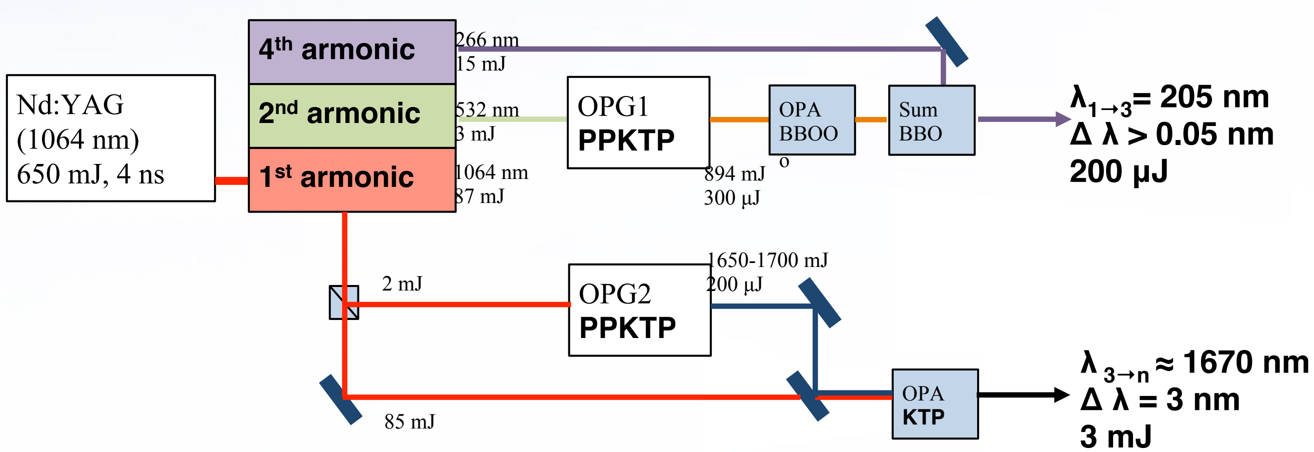
Mariazzi S et al., *Phys. Rev. B* 2010, 81, 235481



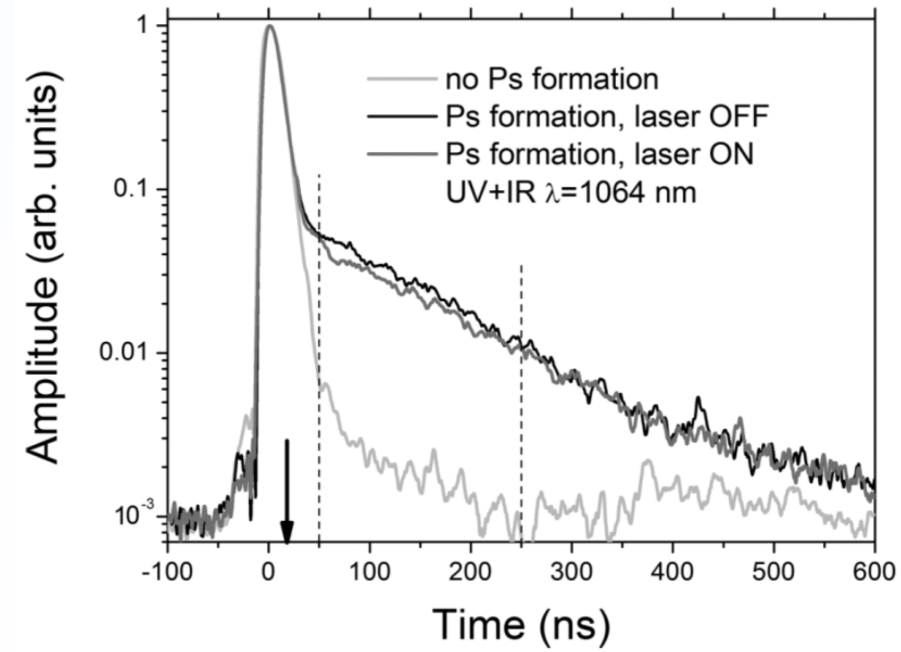
Aghion S et al., NIM B, 362 86–92 (2015)

Demonstration of Ps n=3 laser excitation

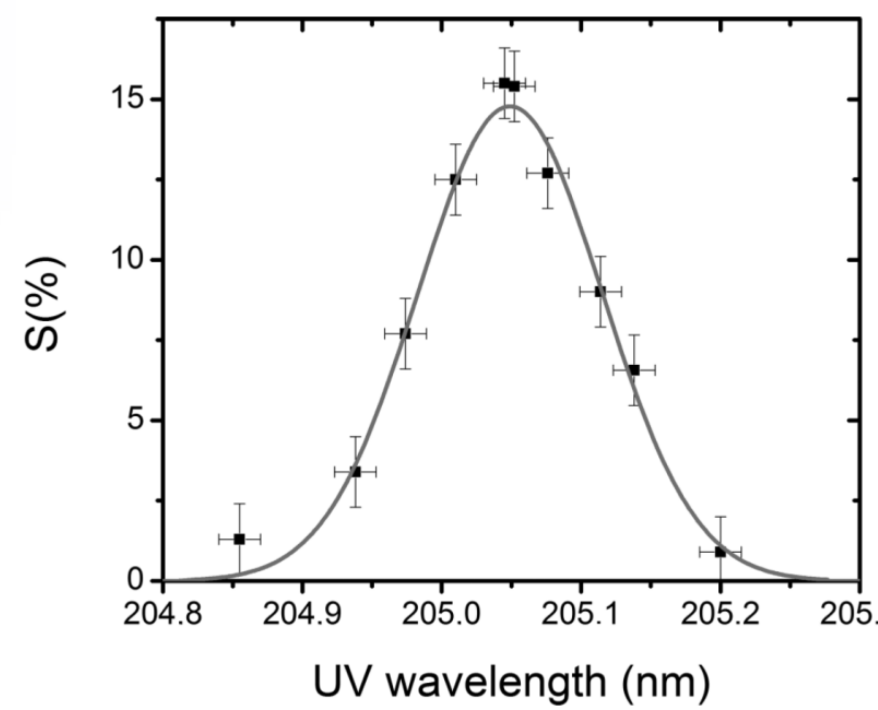
- 3P excitation line centered at 205.05±0.02 nm
- excitation-ionization efficiency ~15% (determined by ionization by IR pulse)
- Evidence for n=15-18 Rydberg excitation by 2-step laser excitation



Method: Cialdi S. et al., NIMB 2011, 269, 1527.

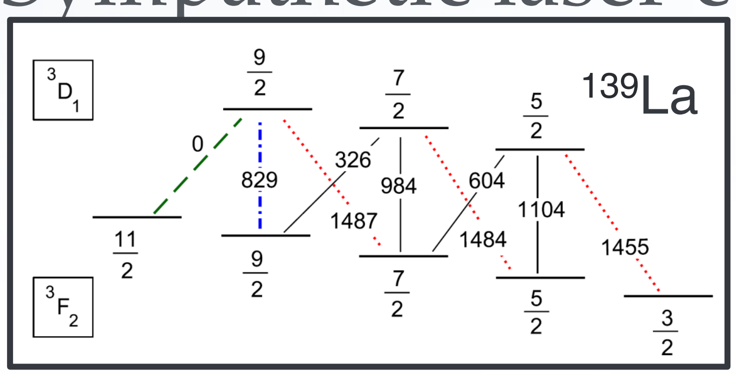


S(%)=(Area laser OFF-Area laser ON)/Area laser OFF

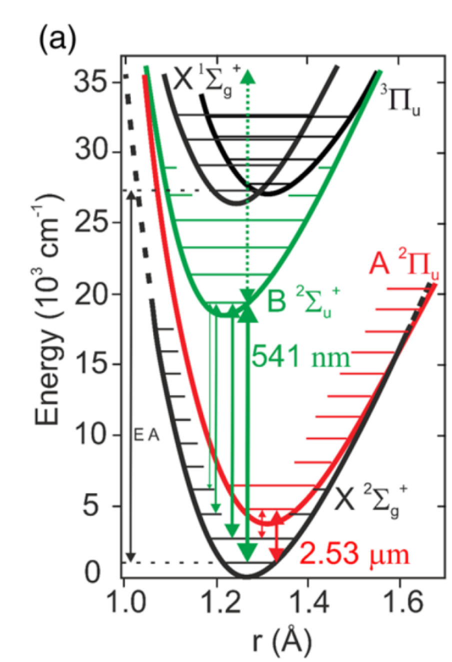


Cooling of p

- Cold p to maximize flux
  - Final goal: T ~100 mK, 1st phase T ~ 7 K
- Cooling mechanisms
  - Radiative electron cooling
  - Evaporative / adiabatic p cooling
  - Sympathetic resistive cooling of p with e^- cooled by resistive cooling
  - Sympathetic laser cooling with negative ions



E. Jordan et al., PRL ***115*** *113001 (2015)*



- Sympathetic cooling with C↓2↑−

P. Yzombard et al., PRL. ***114*** *213001 (2015)*

Summary

- AEg IS aims at first ever direct measurement of deflection of antihydrogen beam by the Earth's gravitational field
  - Test of WEP with antimatter
- Milestone Ps excitation achieved
- Experiment is taking beam
  - 2016 goal: H production at T~7 K (current min. temperature)
    - later stage → 100 mK
  - H beam production
  - Gravity measurement
  - H -HFS spectroscopy

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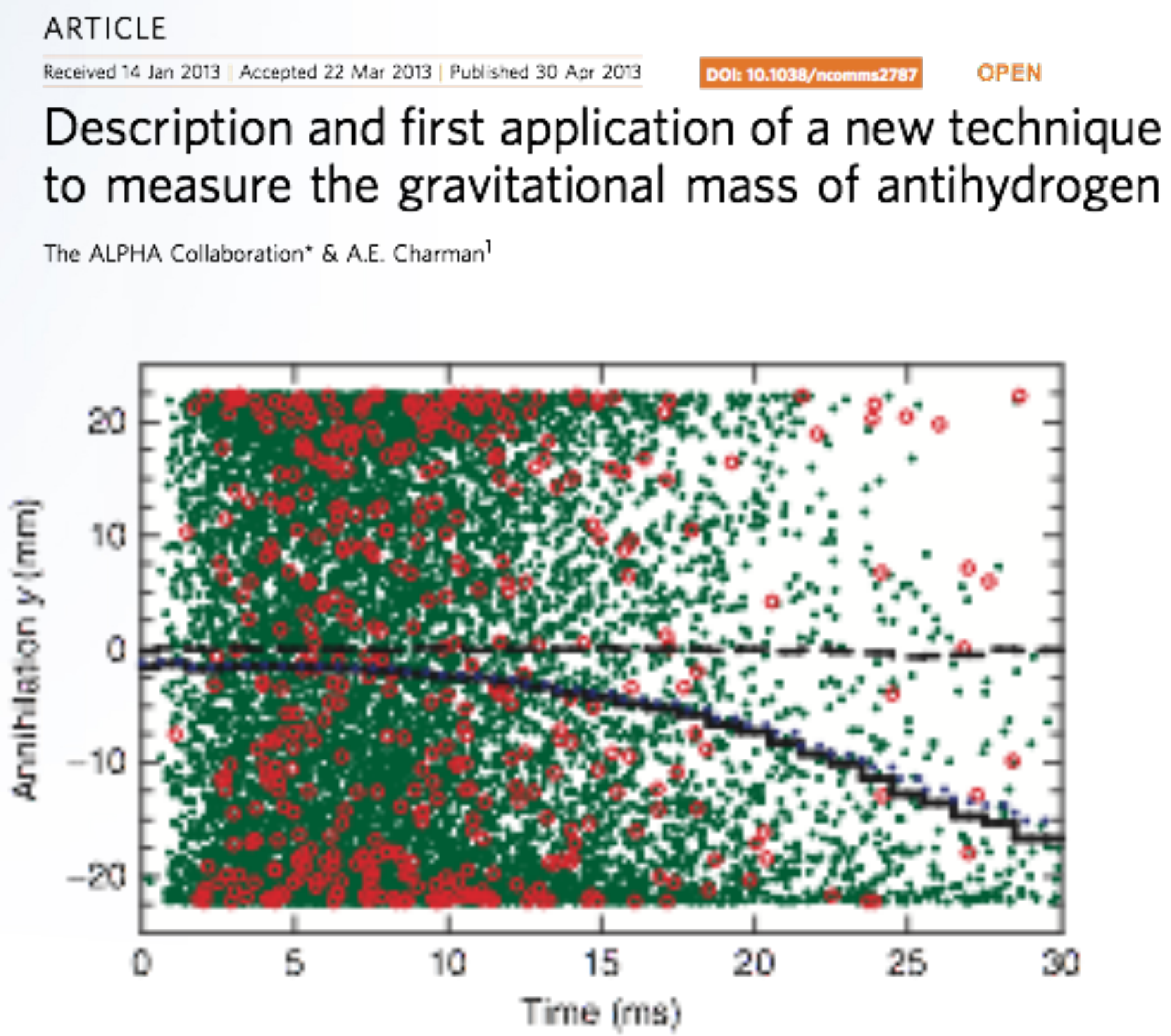
Hyperfine Structure of Antihydrogen

AEg IS results

ALPHA GRAVITY MEASUREMENT

- release trapped $\bar{H}$
- too hot for gravitational force
  - limits on ratio inertial and gravitational mass
- Gravity
  - no systematics
  - $m_{grav}/m_{inertial} < 75$
  - with systematics
  - $m_{grav}/m_{inertial} < 110$
- Antigravity
  - $m_{grav}/m_{inertial} > -65$



Gravitational redshift of clocks

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).

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

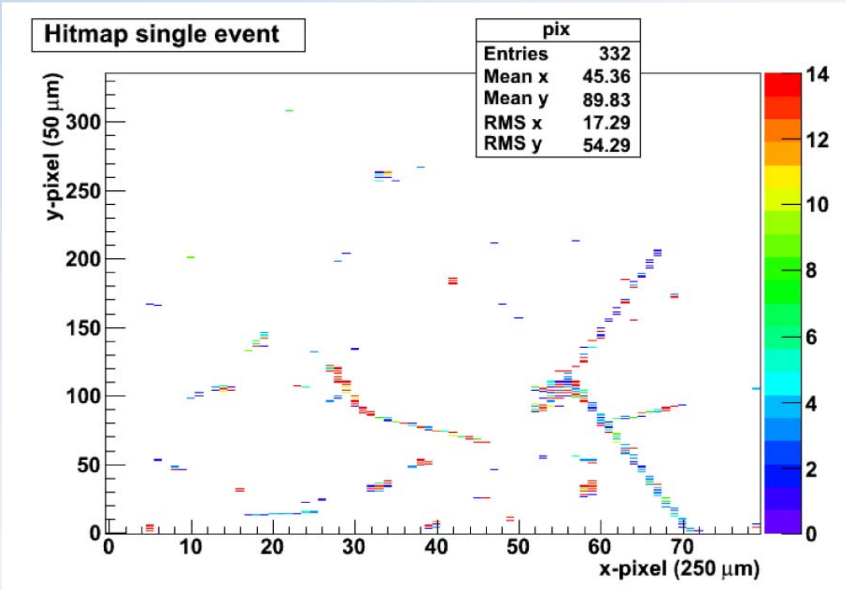
TRAP collaboration G. Gabrielse

Hyperfine Structure of Antihydrogen

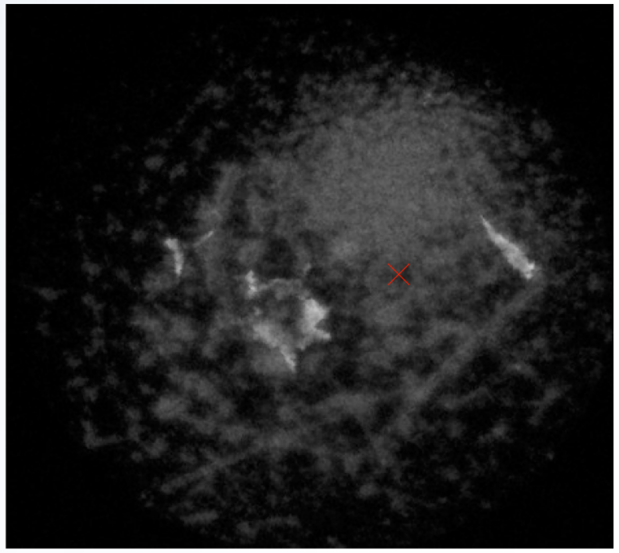
THANK YOU VERY MUCH FOR YOUR ATTENTION!

Gravity measurement - H^- detectors

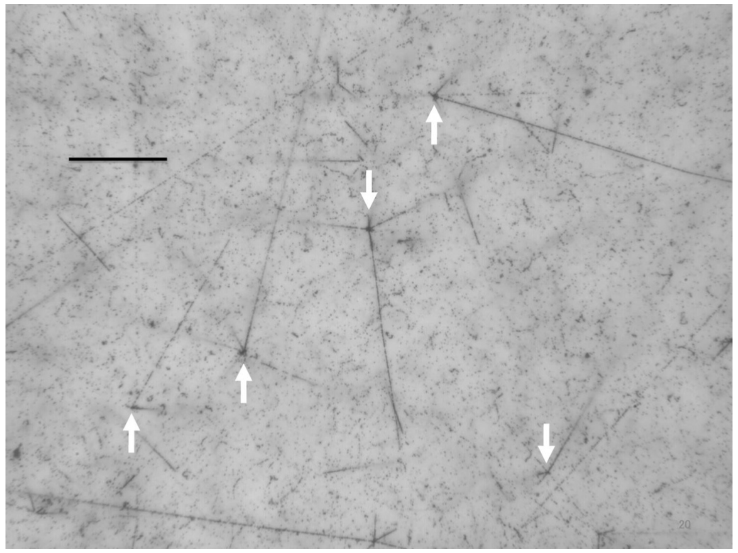
Silicon detectors(strip, pixel)



MCP



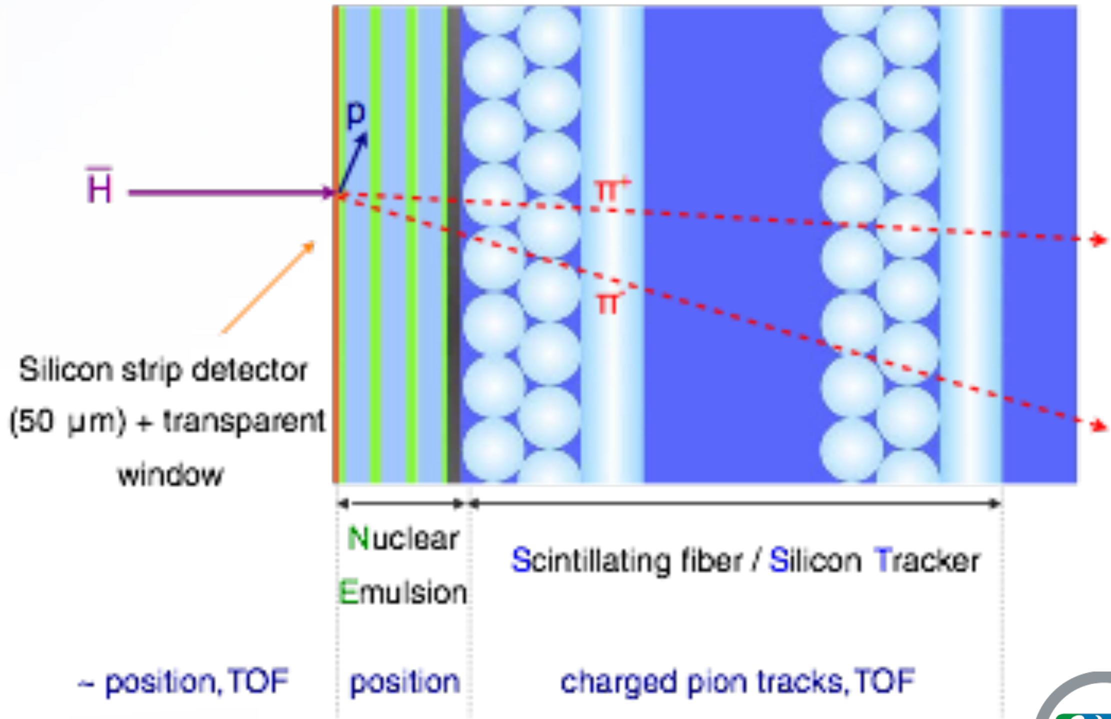
emulsions



Hybrid detector needed

- timing
- position resolution ~10 μm

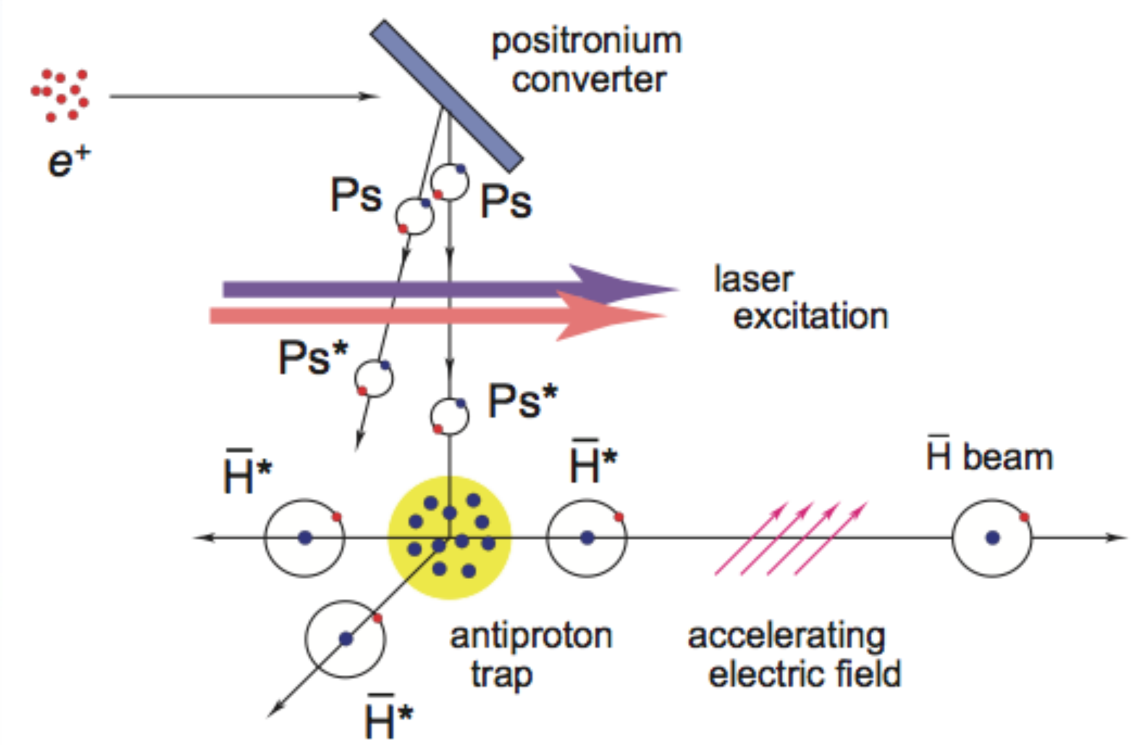
J. Storey et al. Hyp. Int. 0304-3843 (2014)



Production of H atoms

- Charge exchange with Ps^*
  - Capture p from CERN-AD
  - Cool p
  - Ps production by e^+ on SiO_2
  - Ps laser excitation to Rydberg state
  - Interaction Ps^* with p cloud
  - Recombination: resonant charge exchange

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

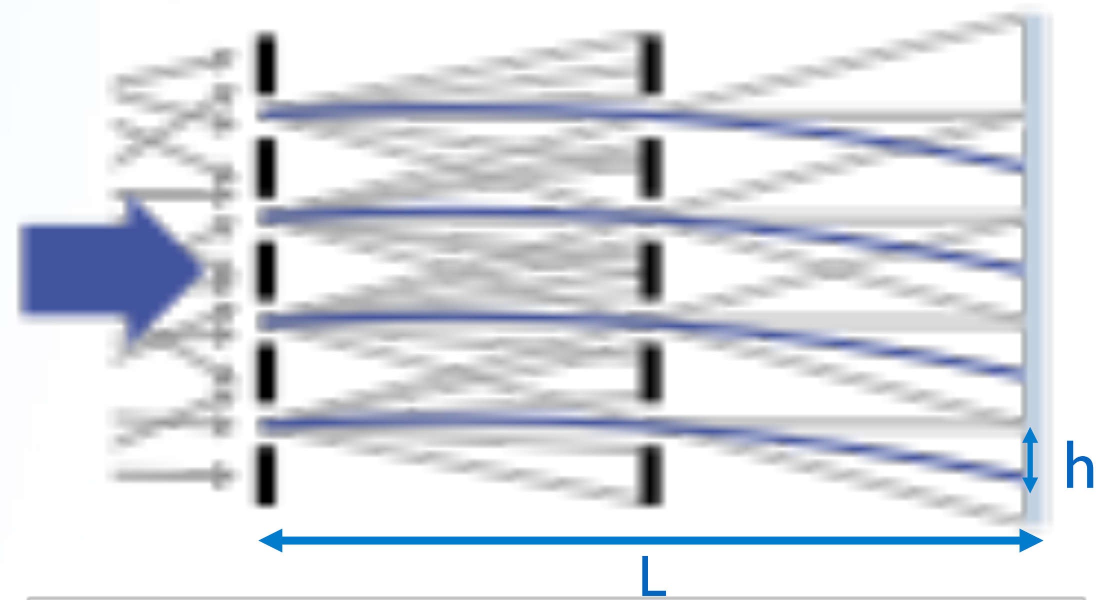


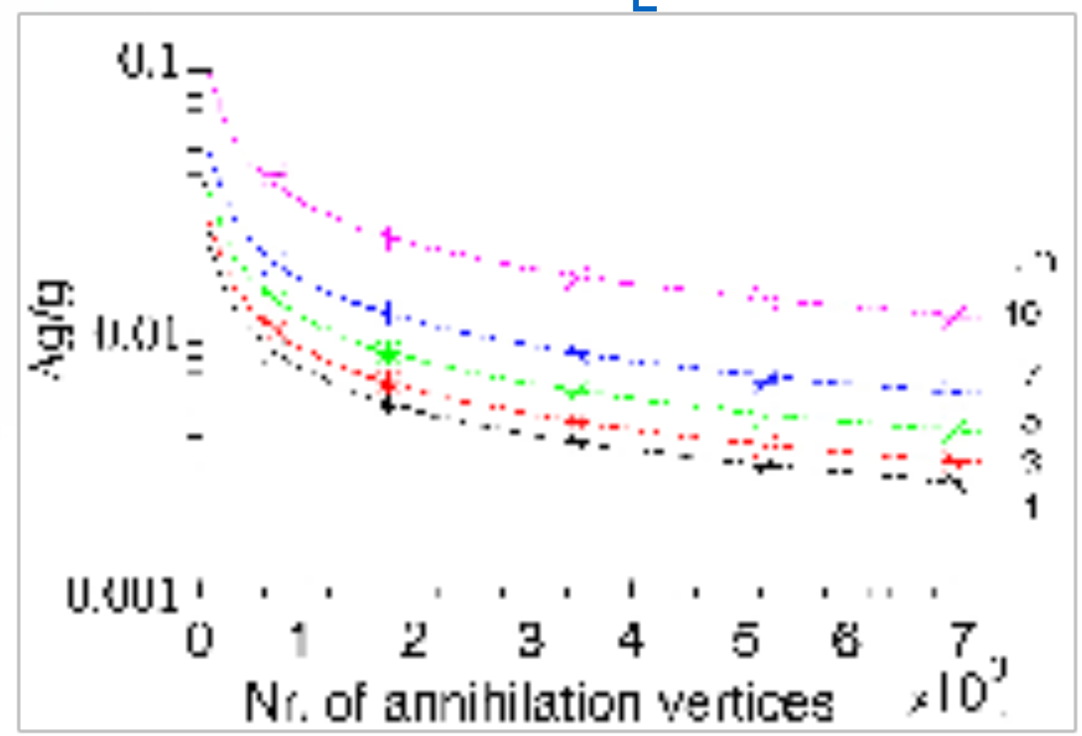
enhanced formation rate:
- $\sigma \sim n^4$
- $Ps(n_1) \rightarrow H\ (n_2)$

H beam & measurement princ

- H beam formation by Stark acceleration
  - v_h ~ 400 m/s
- Measurement of g
  - Two-grating Moiré deflectometer Φ 100mm, L=1m, slit 12 μm, pitch 40 μm, 100 μm thick
  - Position-sensitive annihilation detector Δh≤10μm (emulsion)
  - velocity information needed: pulsed beam & detector with time resolution (TOF~2.5 ms)

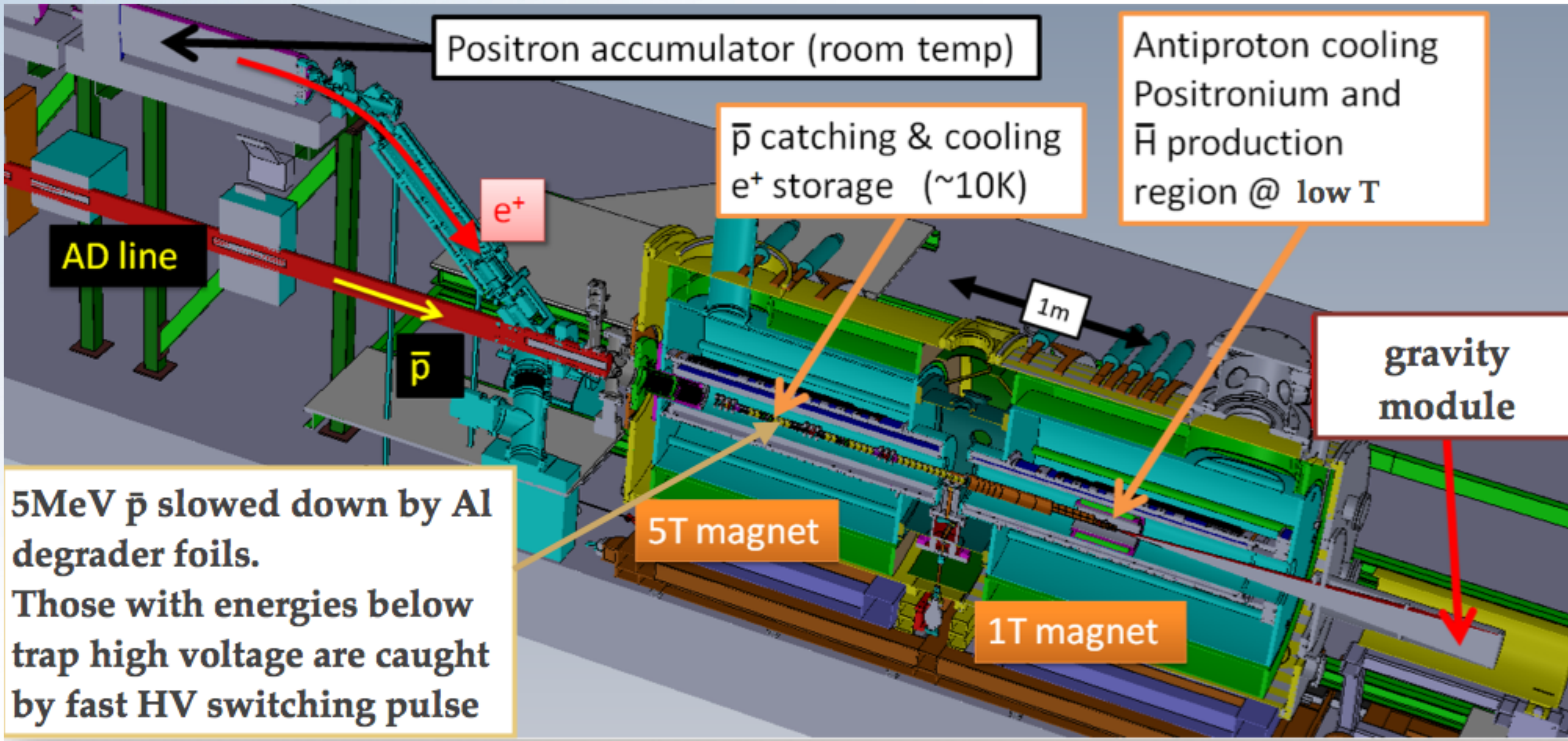
M.K. Oberthaler et al., Phys Rev. A 54, 3165 (1996)





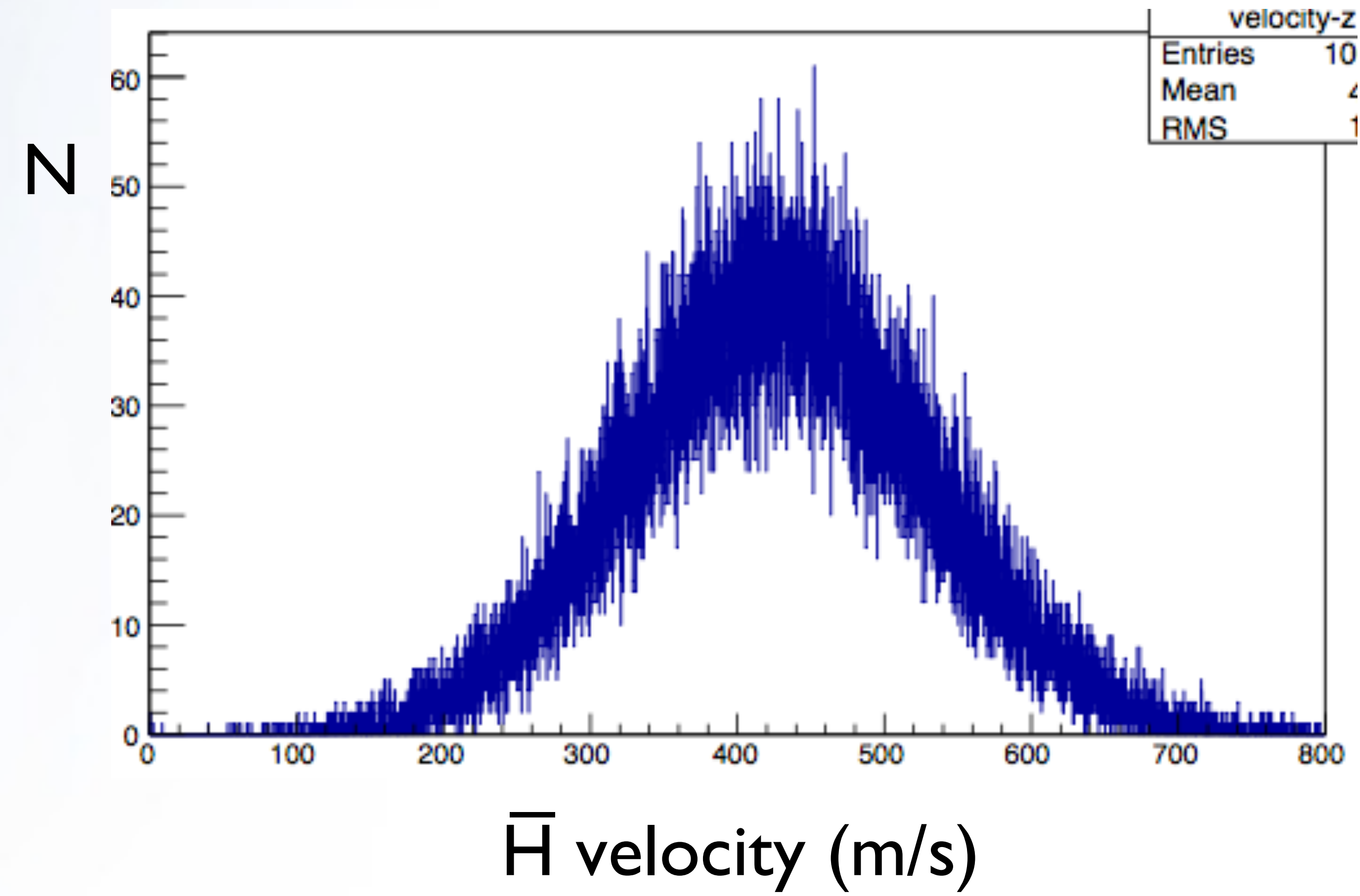
Aghion, S. et al., JINST, 8, P08013 (2013)

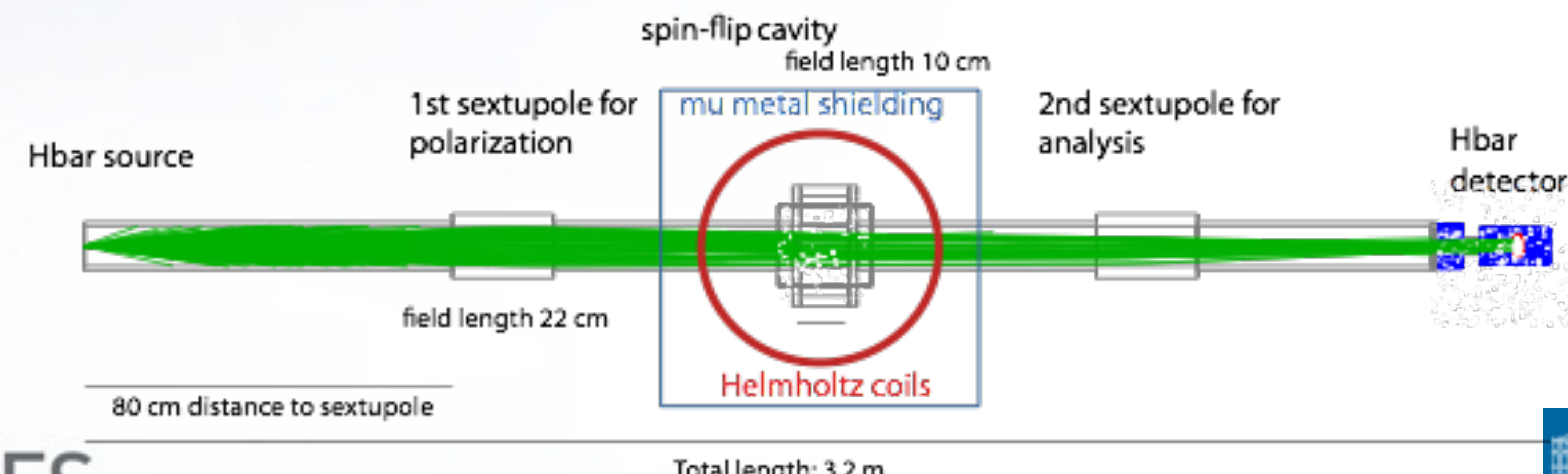
Experimental setup



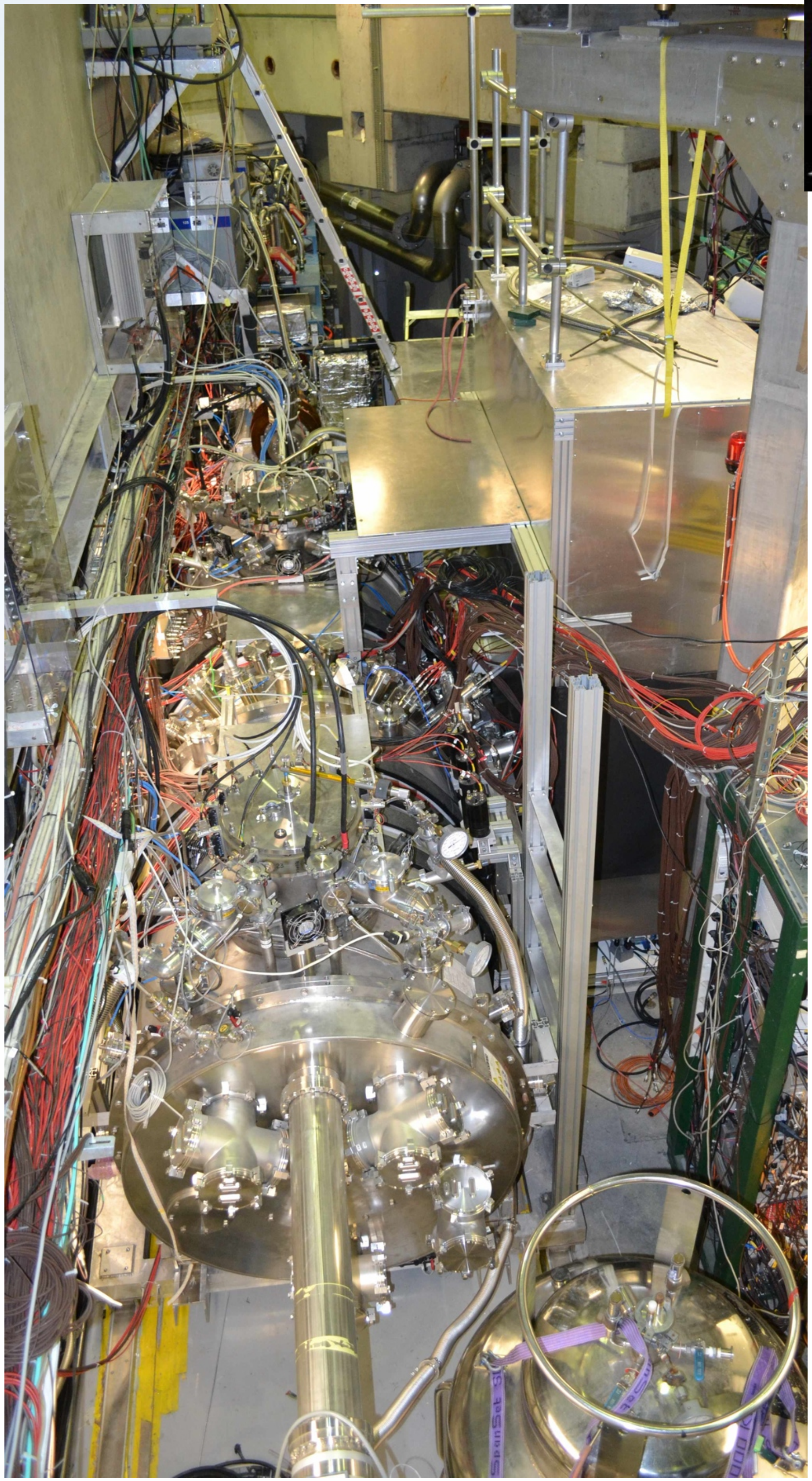
ULTRA-SLOW $\bar{H}$ BEAM

- narrow velocity distribution around 400 m/s
- no polarization: 2nd sextupole needed
- rates similar to CUSP



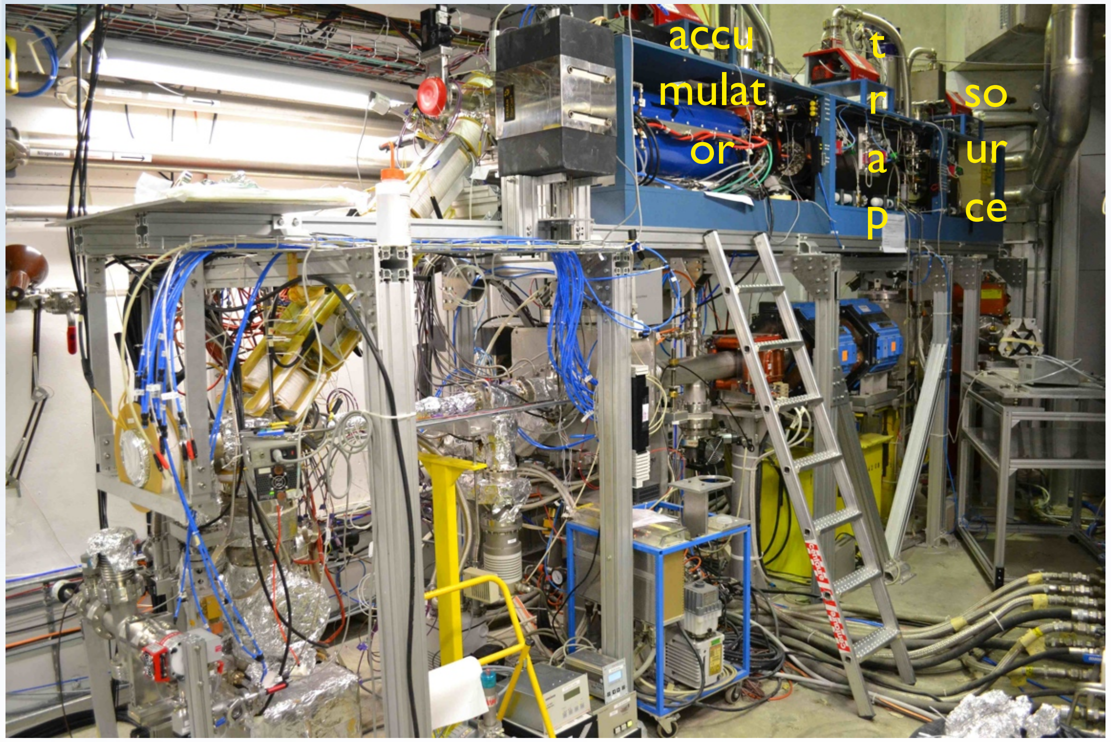


Experimental area

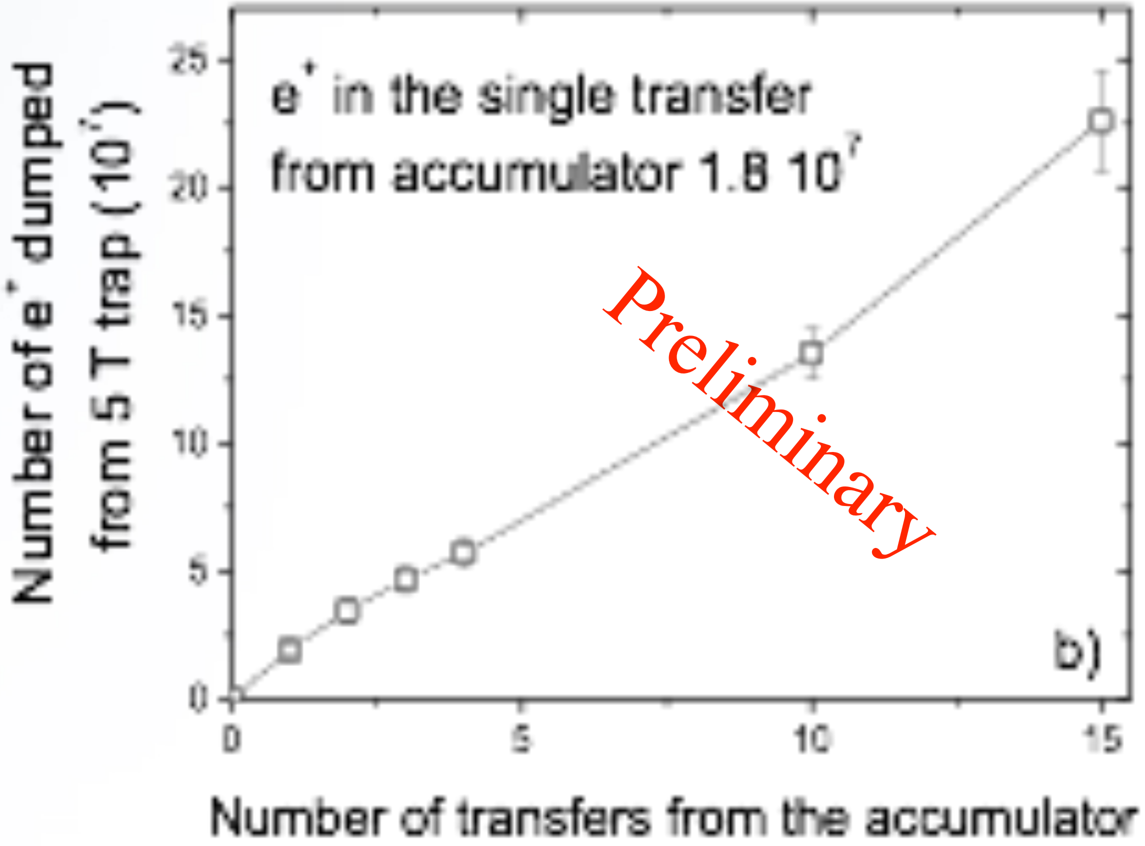


Positron system

- Surko-type e$^+$ accumulator



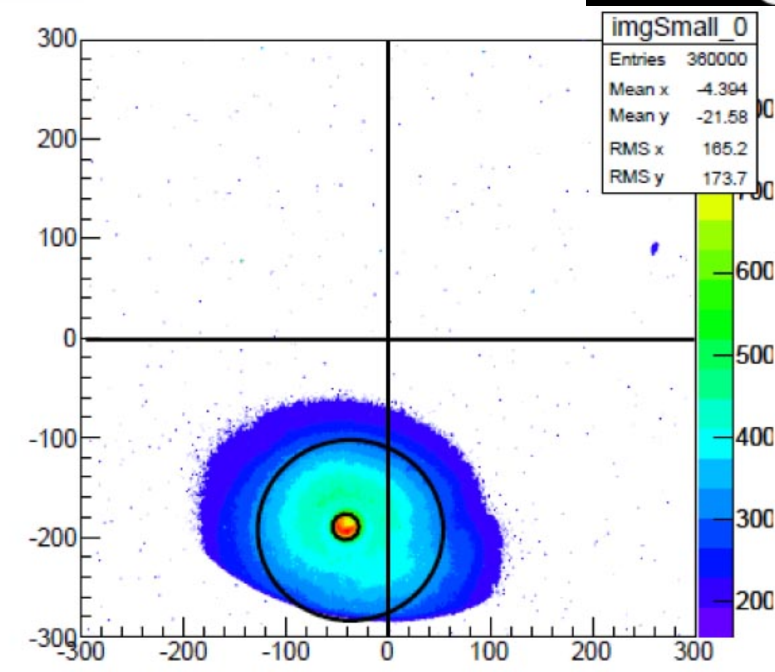
Achieved e$^+$ numbers in 5

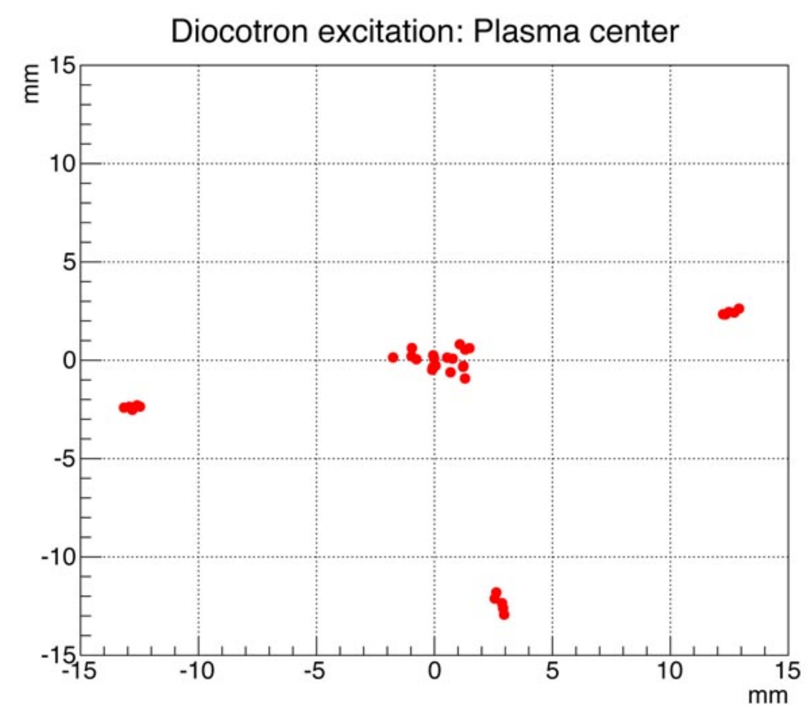


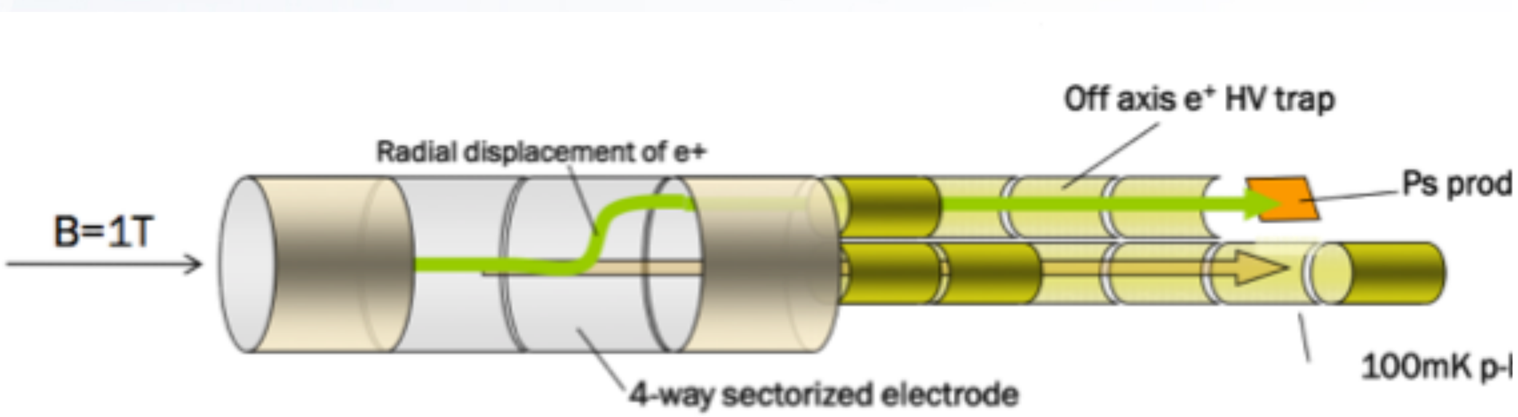
e$^+$ source strength ~10 mCi
total accumulation time ~80 min

e^+ manipulation: tests with e^-

- Rotating wall compression
- Move e^+ off-axis by exciting diocrotron motion

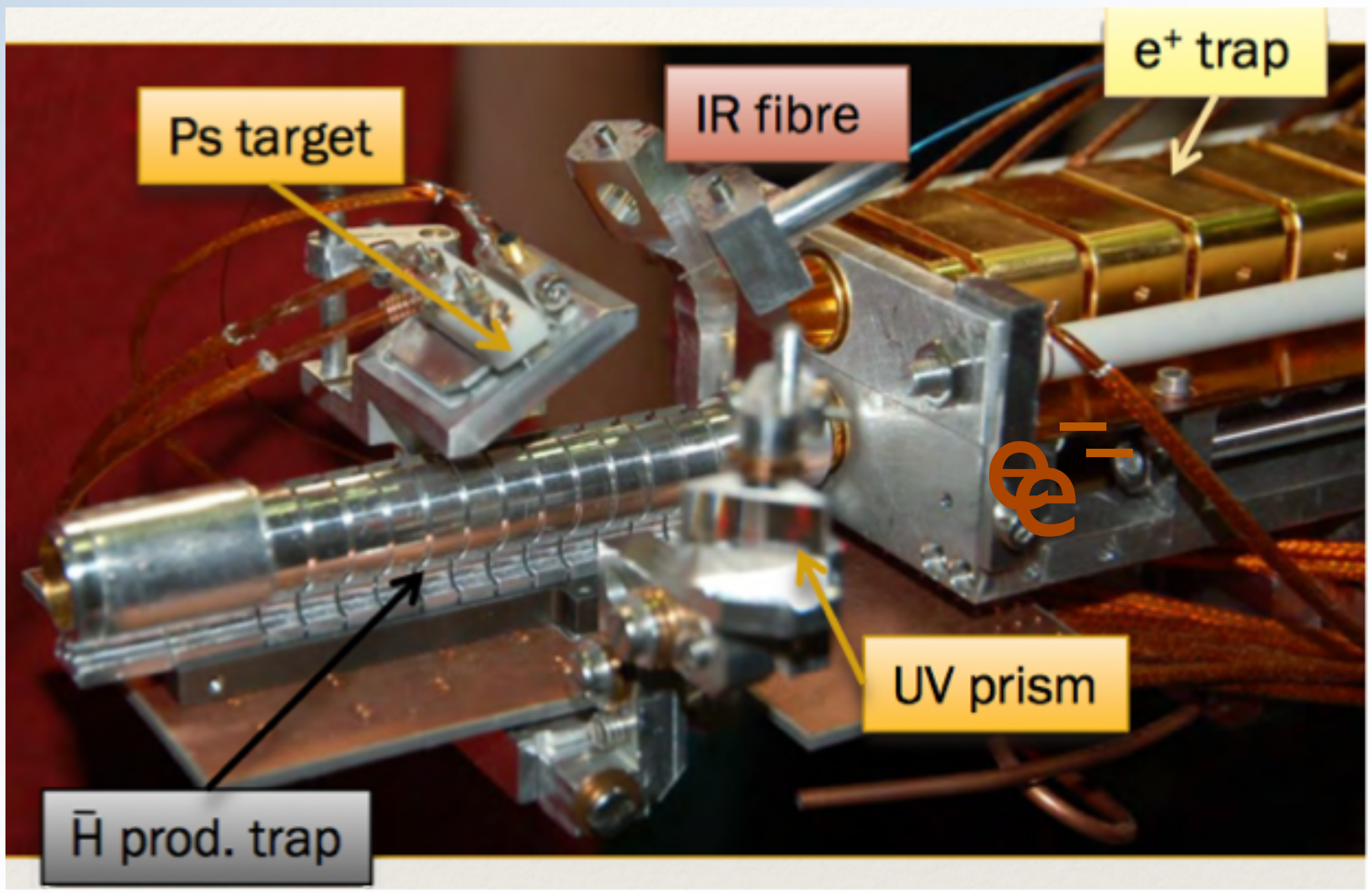


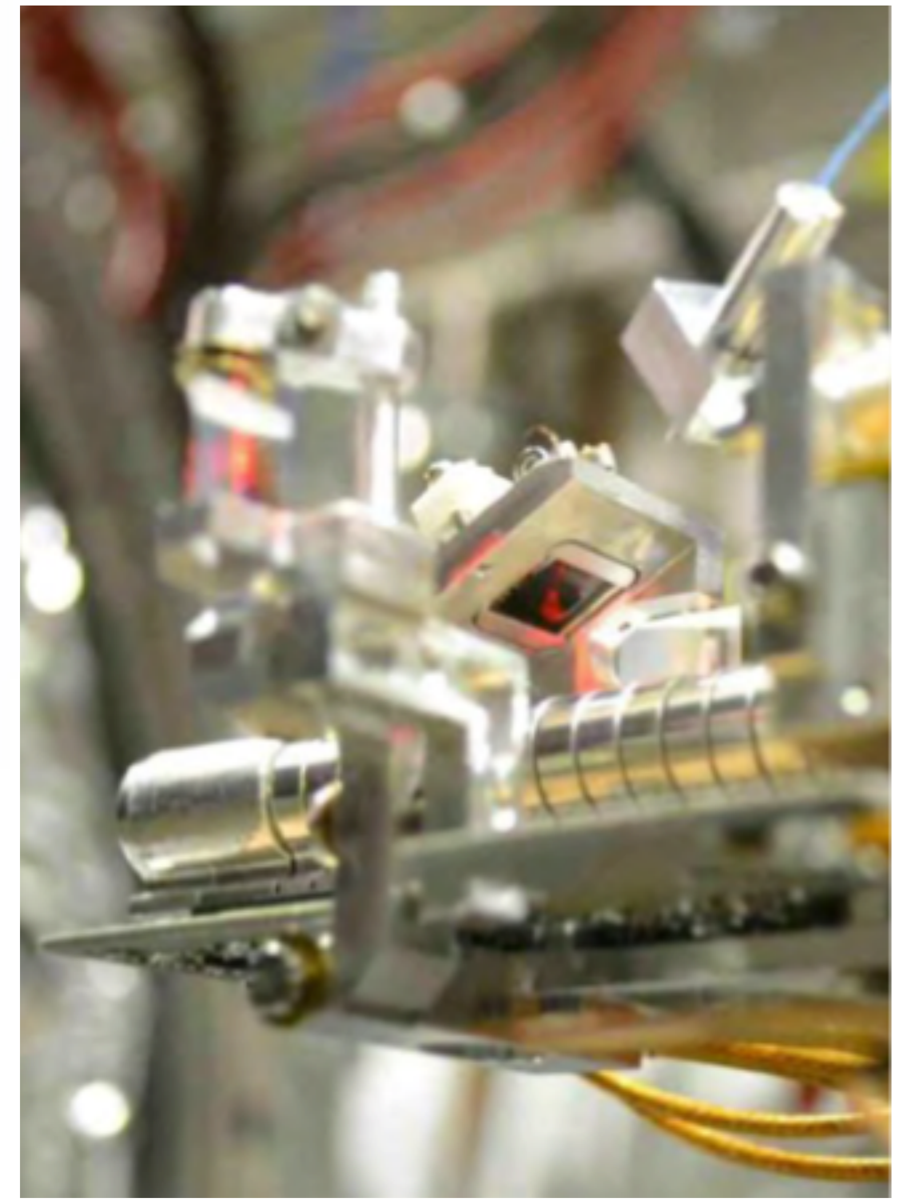




C. Canali et al., Eur. Phys. J. D 65 (3) 499-504 (2011)

Ps and H formation region



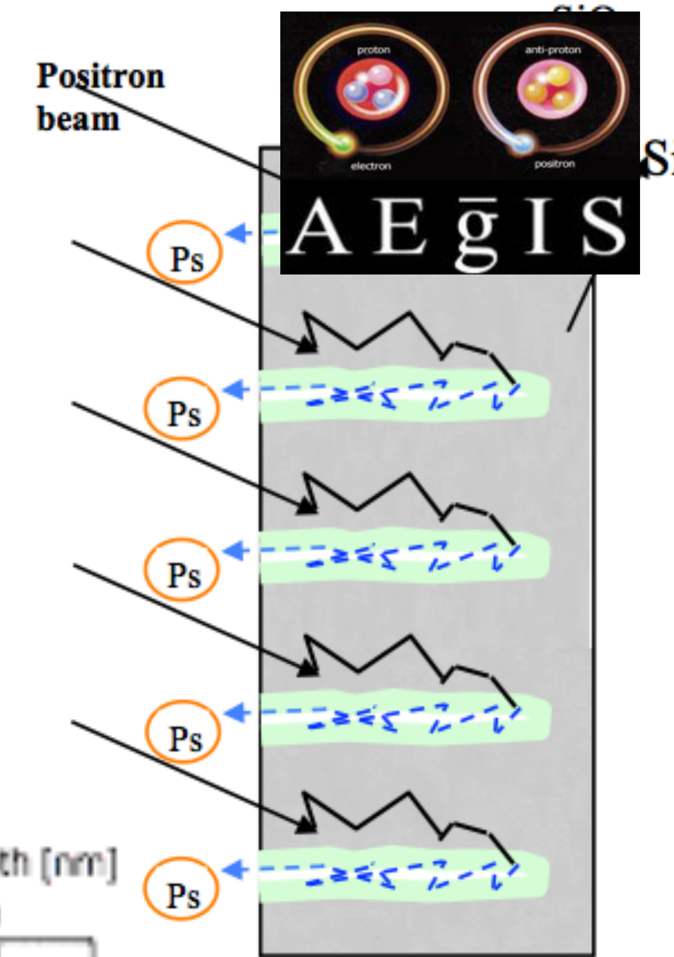


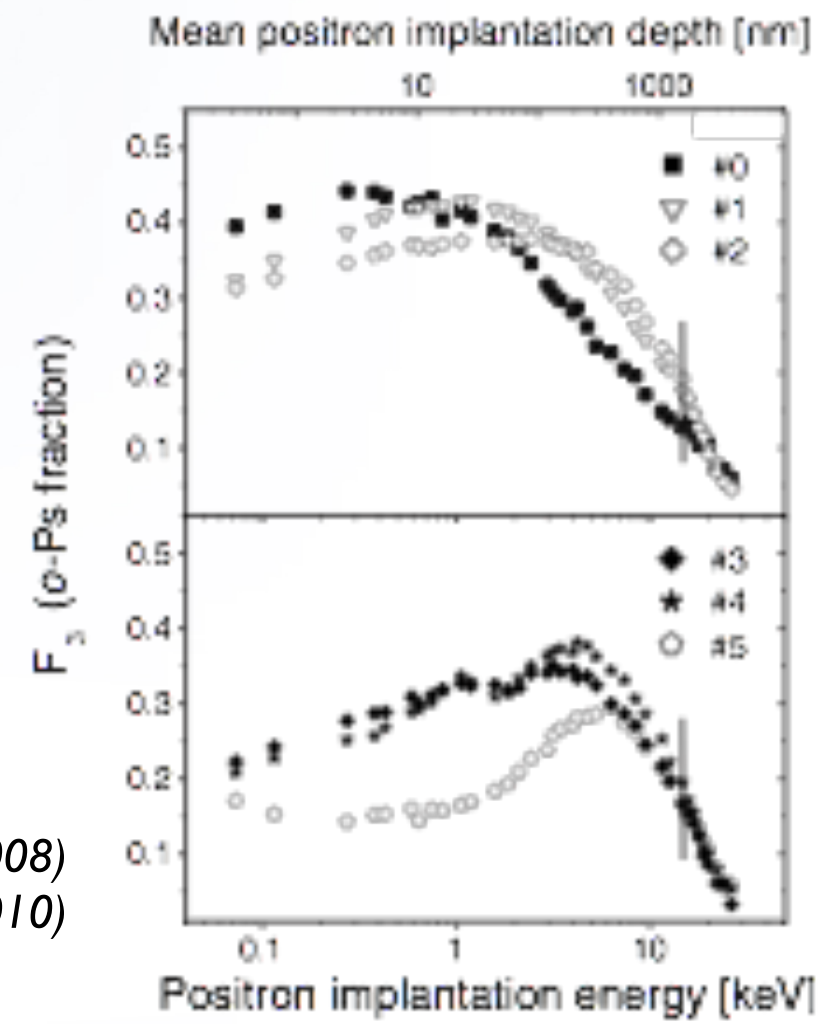
G. Consolati et al., Chem. Soc. Rev. 42, 3821 (2013)

Ps production

- Implantation of e^+ in nano-porous (8–14 nm Φ) silica
  - ~75 K o-Ps needed
  - Large implantation depth
  - High Ps formation rate
  - Possibility to tune nano channel dimensions: tune Ps temperature

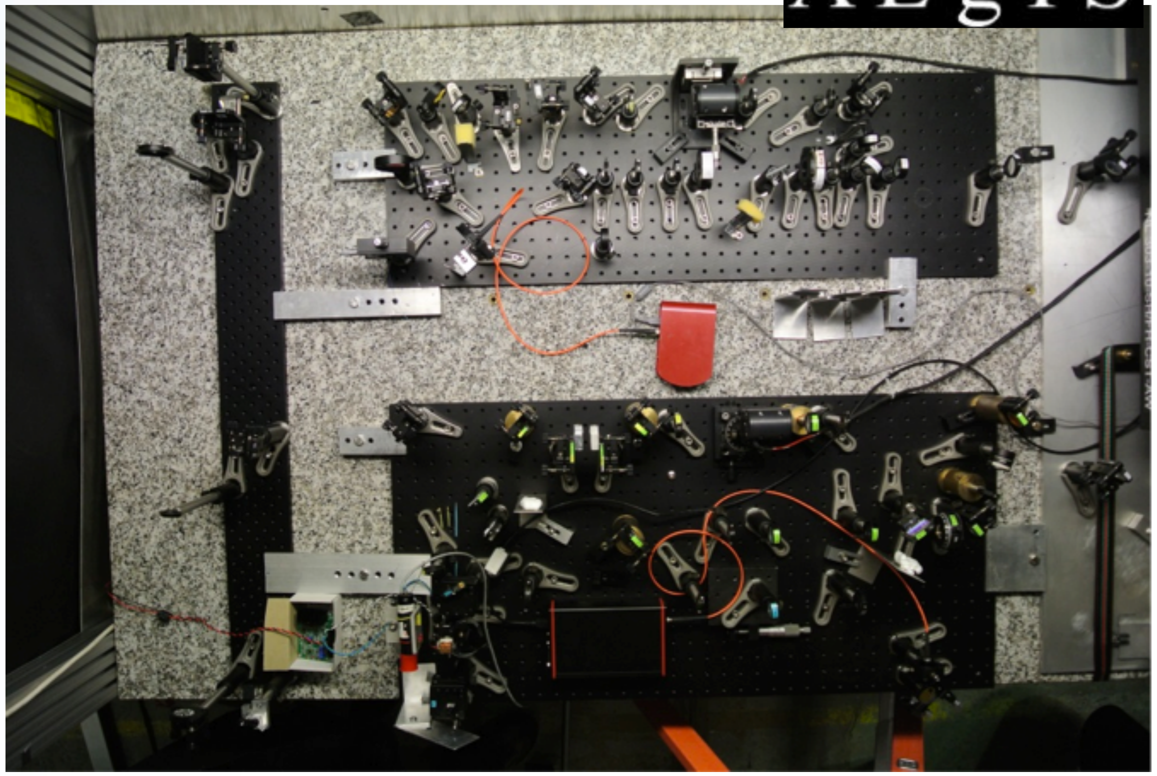
S. Mariazzi et al., Phys. Rev. B 78, 085428 (2008)
S. Mariazzi et al., Phys. Rev. B 81, 235418 (2010)

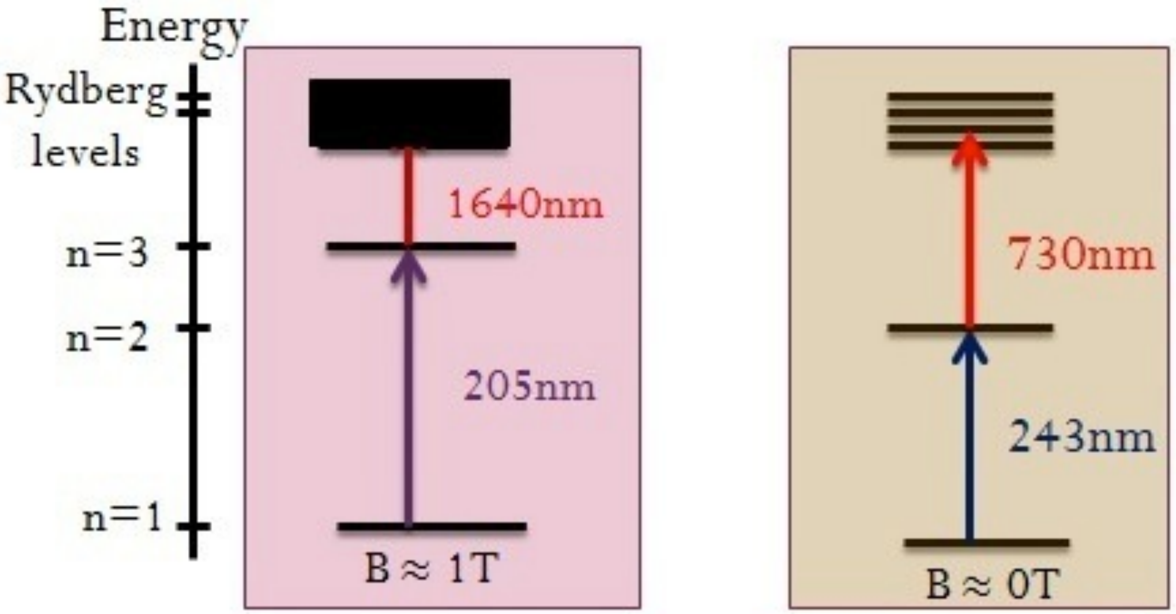




Ps excitation

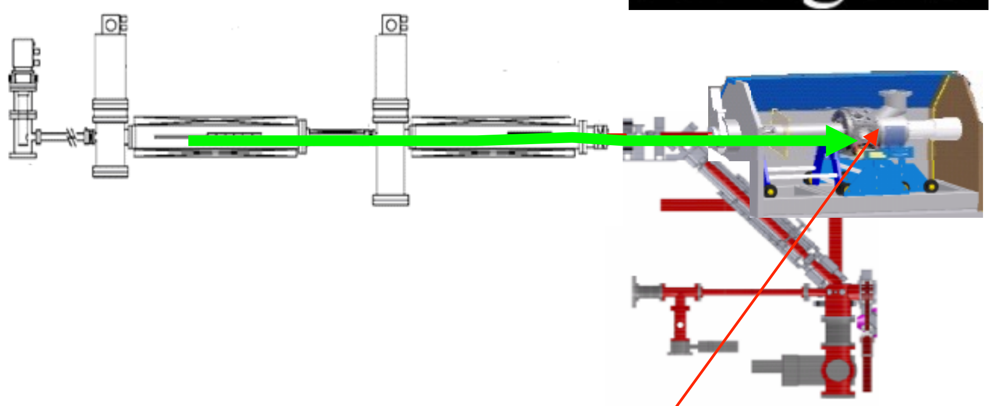
- 2-stage excitation
  - UV: n=1→3
  - IR: n=3→Rydberg (n=26)
  - Alternative: n=1→2 → Ry

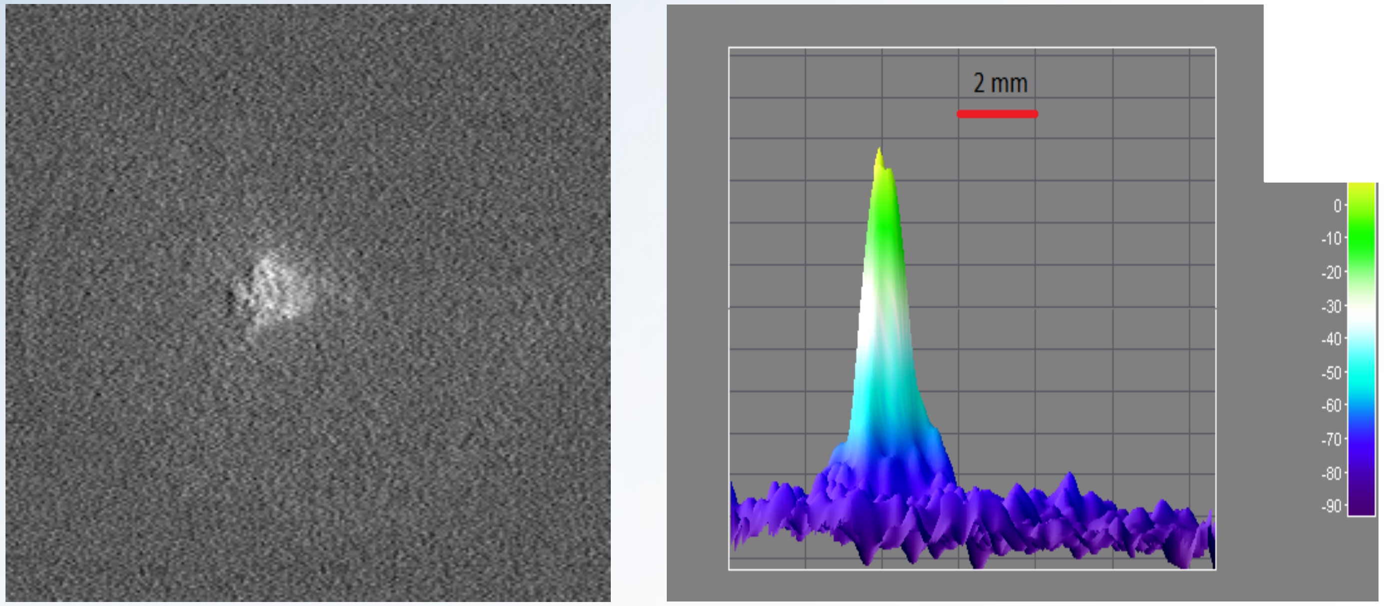




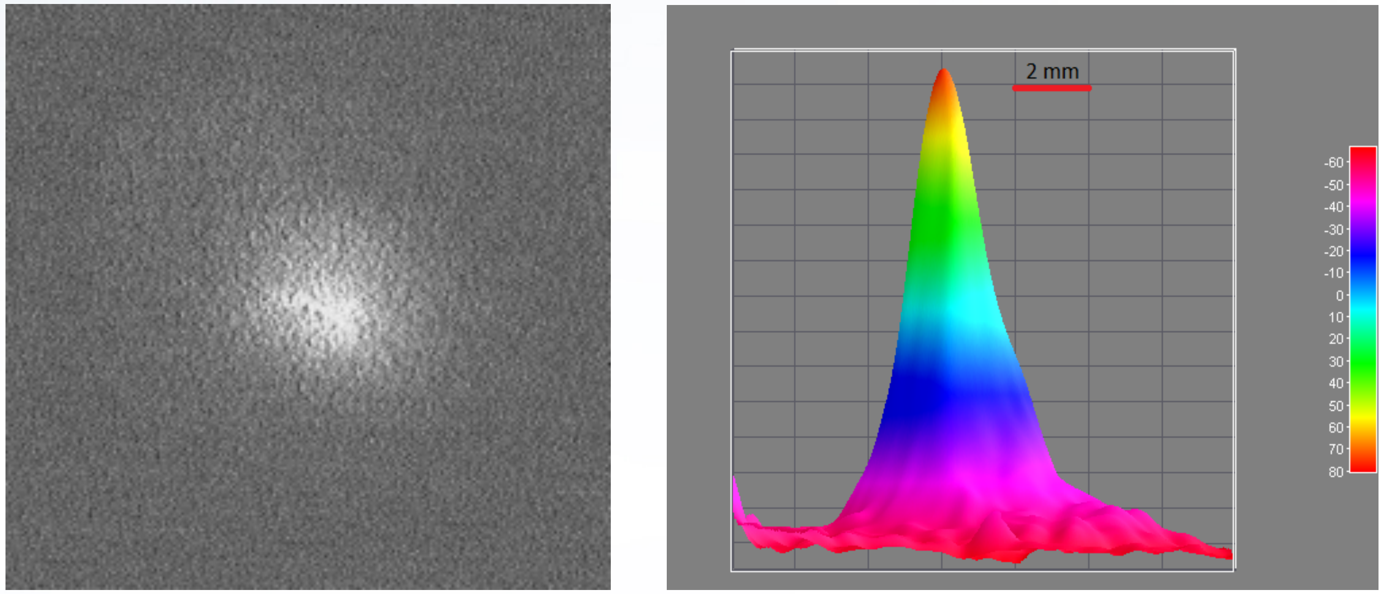
F. Castelli et al., Phys. Rev. B 78, 052512 (2008)
U. Warring et al., Phys. Rev. Lett. 102, 043001 (2009)

Chamber for Ps experiments: focus





No field in the target region.
FWTM <4 mm



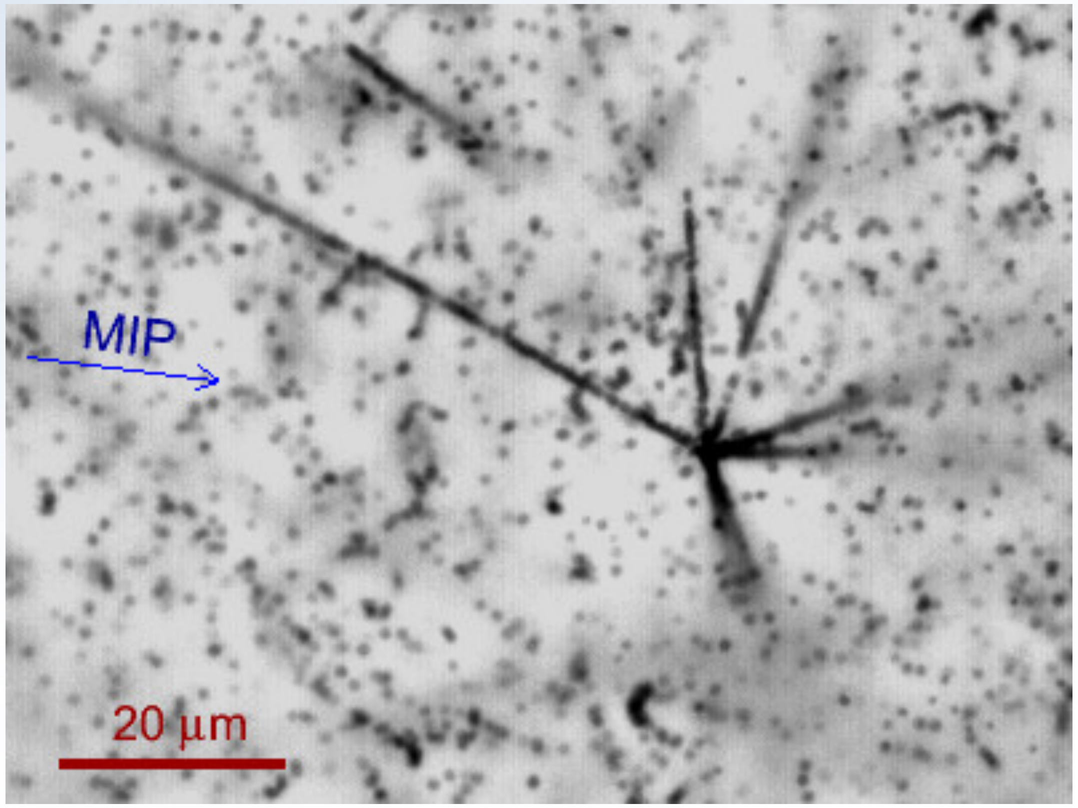
250 Gauss in the target region.
FWTM 5 mm

Aghion S et al., NIM B, 362 86–92 (2015)

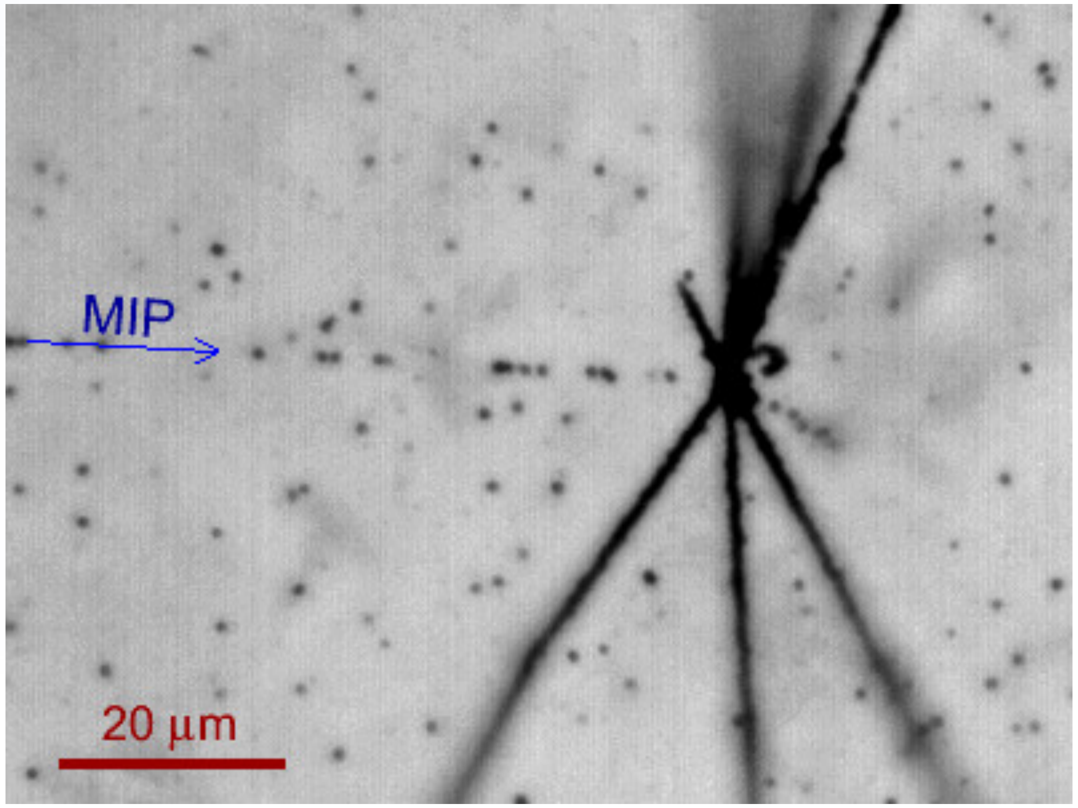
Gravity measurement - H^- detectors

- Emulsion detectors at low temperatures and in vacuum

current emulsion



test emulsion

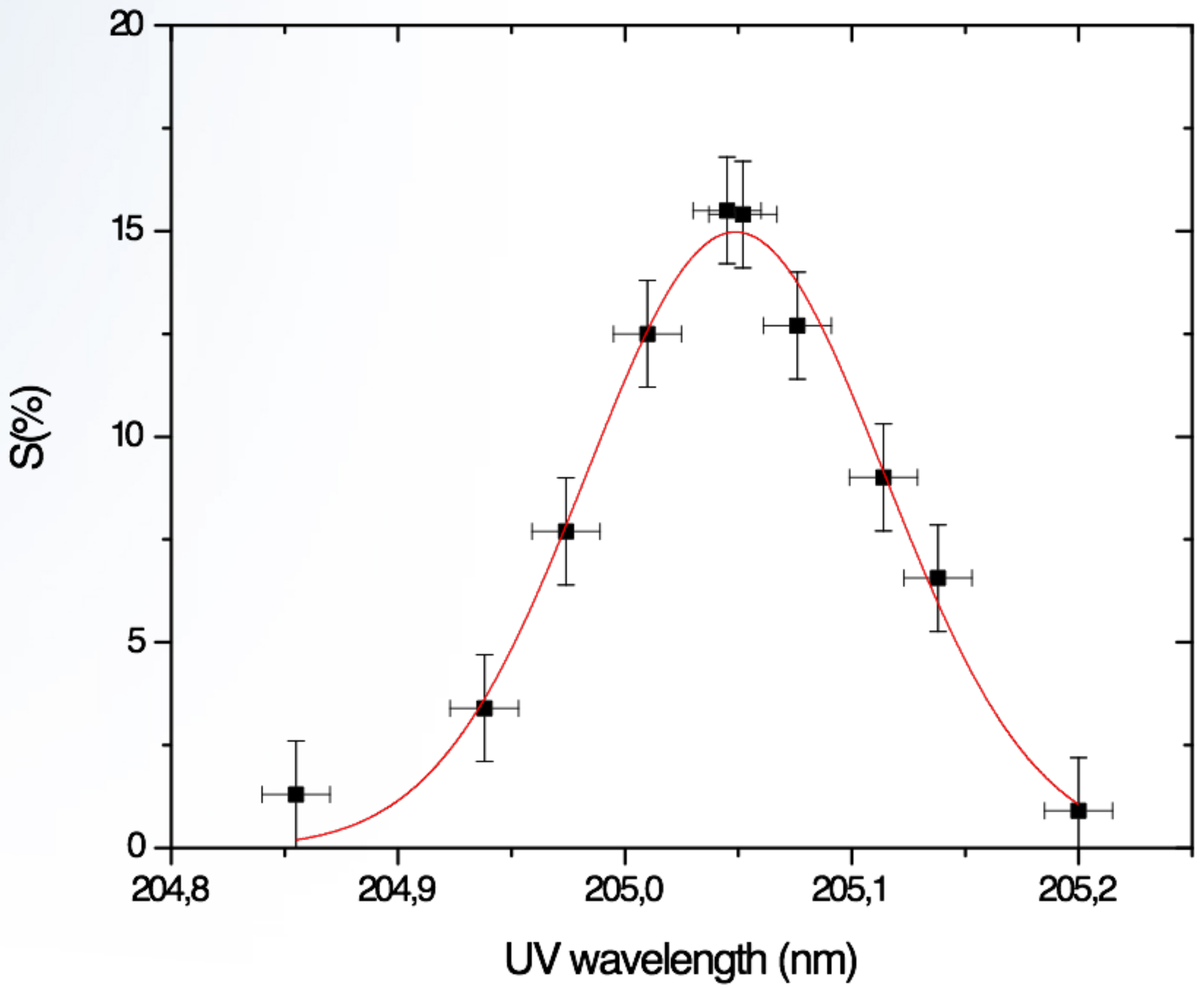


C. Amsler et al. JINST 8, P02015 (2013), S. Aghion et al., JINST 8, P08013 (2013)

Ps n=3 laser excitation

AEgIS

- 3P excitation line centered at 205.05±0.02 nm
- excitation-ionization efficiency ~15%

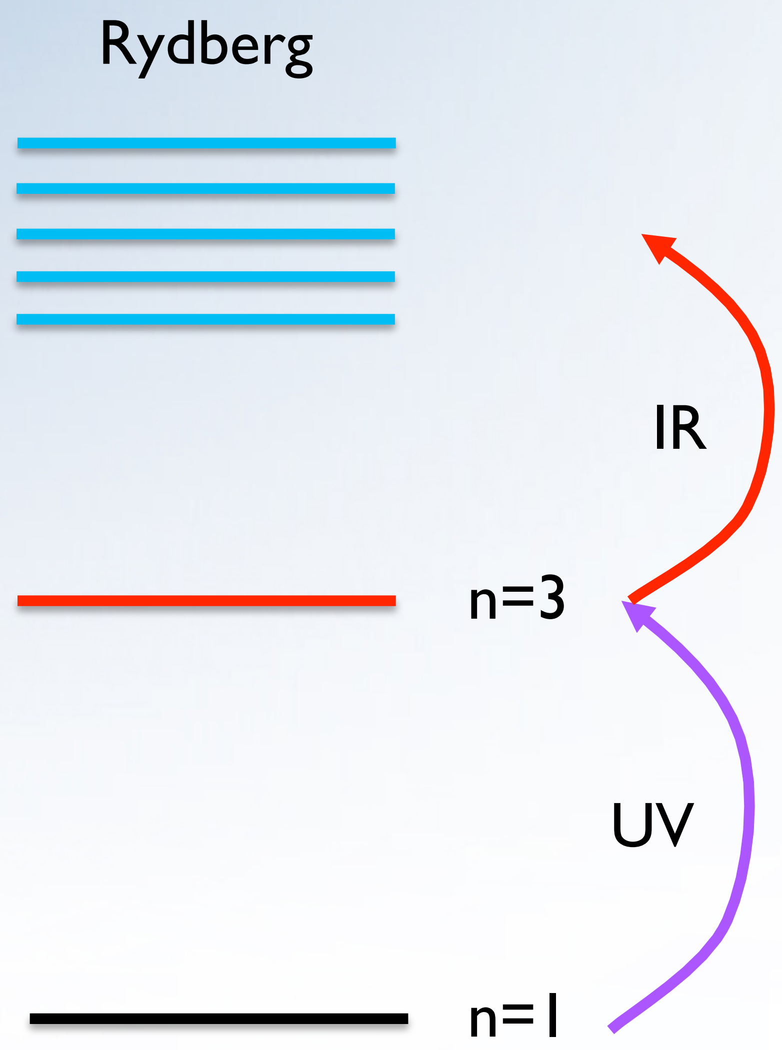


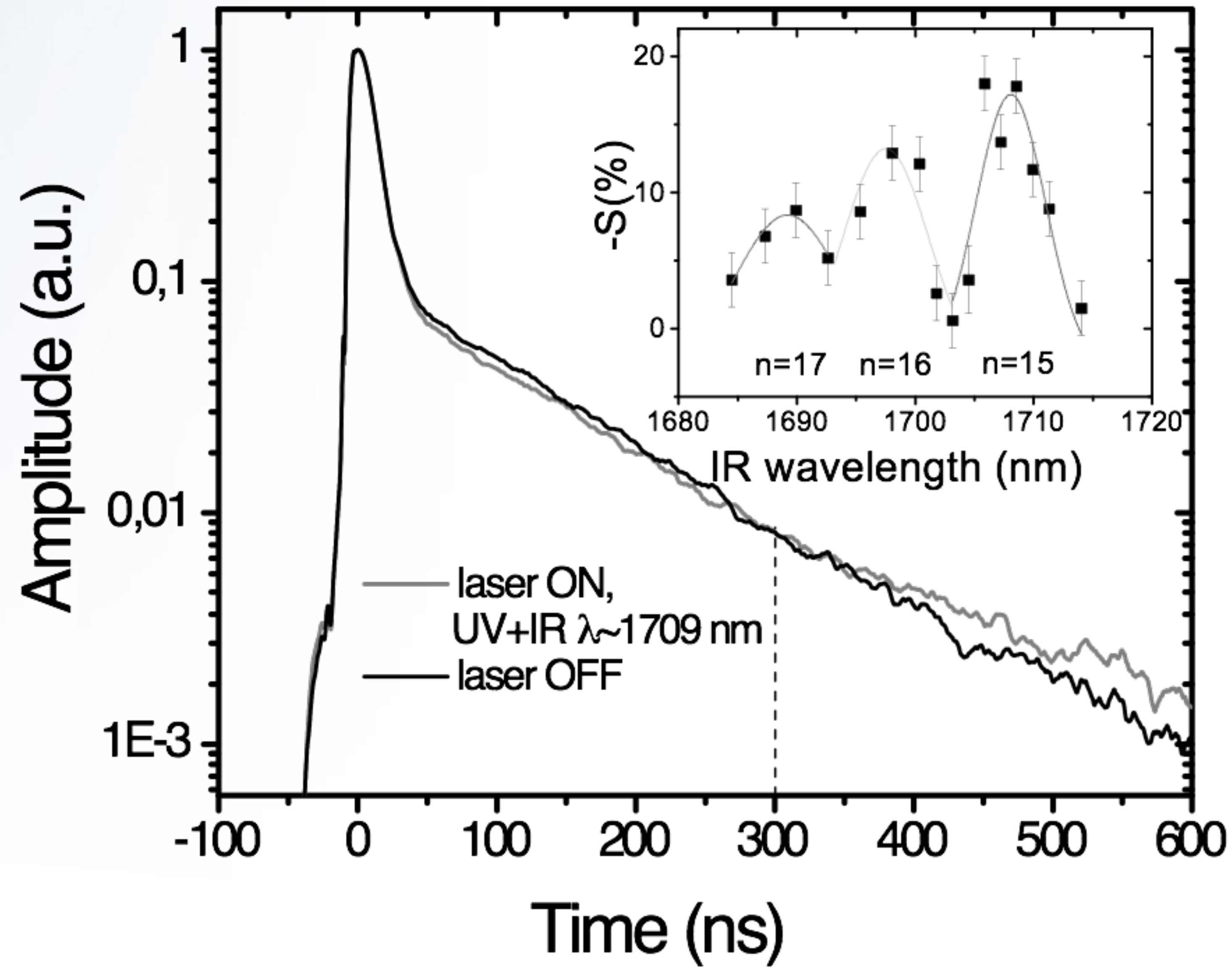
S(%)=(Area laser OFF-Area laser ON)/Area laser OFF

Aghion S et al., submitted for publication

Aghion S et al., *PRL*, to be submitted

Ps Rydberg excitation

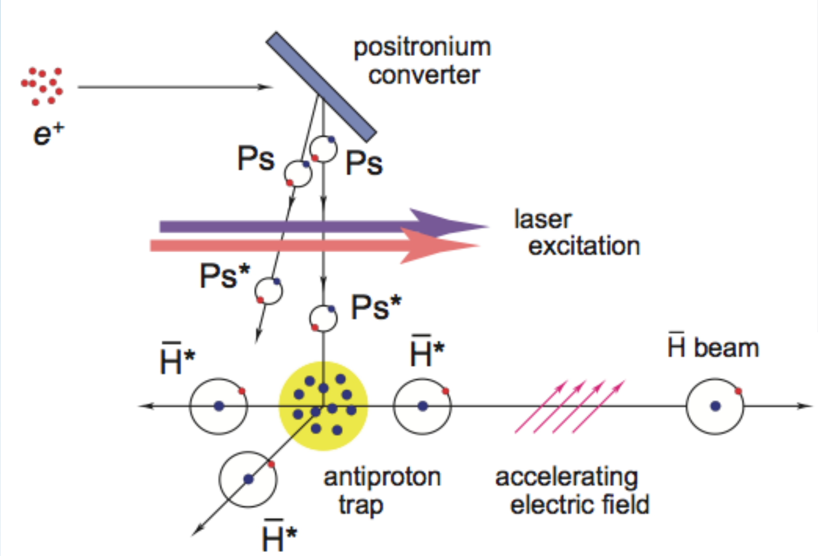




S(%)=(Area laser OFF-Area laser ON)/Area laser OFF

Aghion S et al., CERN-PH-EP-2015-265

AEg IS principle



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