MEASURING $\bar{g}$ WITH AE$\bar{g}$IS

PROGRESS AND PERSPECTIVES

Daniel Krasnický[1] on behalf of the AEgIS collaboration[2]

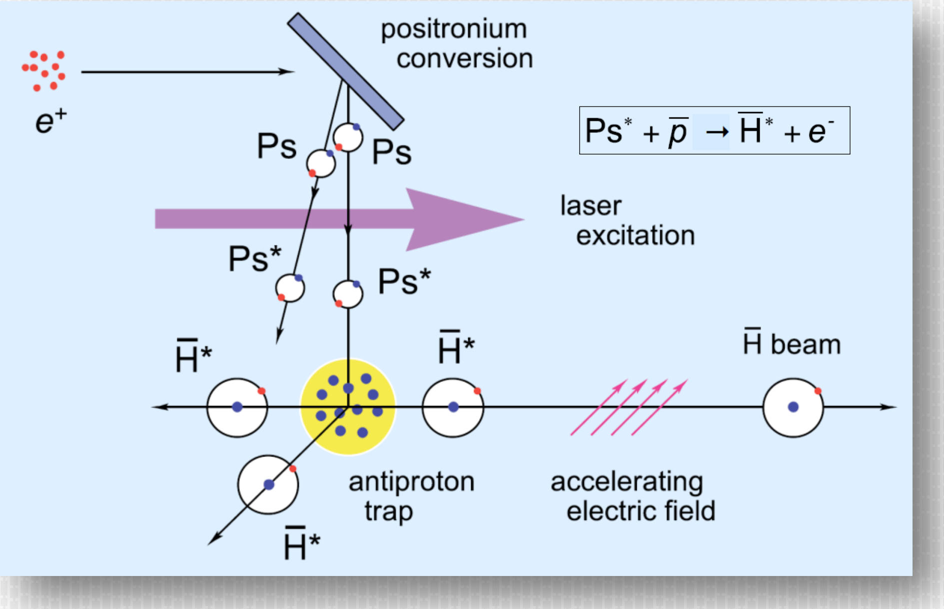
[1] INFN - sezione di Genova, Università di Genova, Via Dodecaneso 33, 16146 Genova, Italy
[2] http://cern.ch/aegis

ANTIMATTER EXPERIMENT: GRAVITY, INTERFEROMETRY, SPECTROSCOPY

- First goal is to measure $\bar{g}$ $(g_{\overline{H}})$ to 1% accuracy
- Test of WEP on antimatter in Earth's gravitational field
- Direct measurement of $\bar{g}$ - free of any assumptions
- Our method:
  - Produce 100mK antihydrogen via reaction $\boxed{Ps^* + \overline{p} \rightarrow \overline{H}^* + e^-}$
  - Accelerate antihydrogen into a neutral beam
  - Measure the gravitational deflection of such cold $\overline{\mathrm{H}}$ beam

ANTIHYDROGEN PRODUCTION & BEAM FORMATION

AEgIS proposal, http://cdsweb.cern.ch/record/1037532



Antihydrogen at 100mK → $v_H \approx 40$ m/s

- o-Ps produced by impact of e^+ on SiO_2 target
- Ps laser excited into Rydberg levels
- Rydberg Ps interacts with a cloud of cold antiprotons trapped in a penning trap and forms $\bar{\mathrm{H}}$ through charge exchange reaction

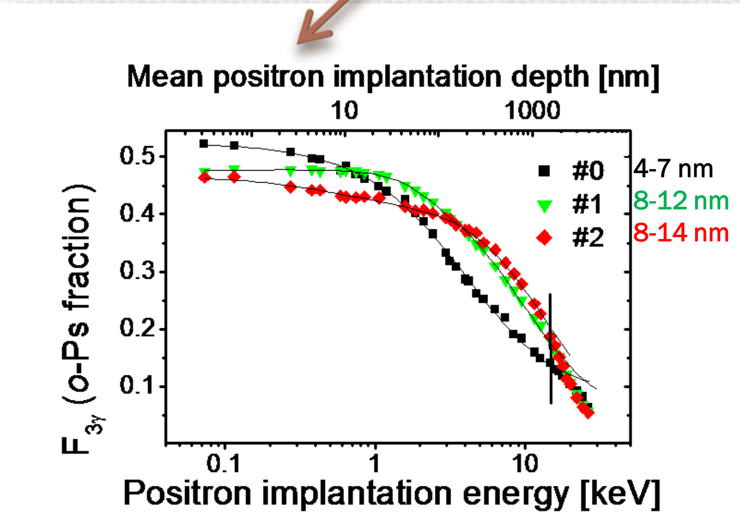
$\sigma \propto n^4$ $\sigma(n_{Ps}=20) \approx 10^{-9}\,\mathrm{cm}^2$

- Antihydrogen state defined by Ps state
- $\bar{\mathrm{H}}$ temperature defined by $\bar{p}$ temperature
- Stark acceleration: Rydberg atoms are sensitive to el. field gradients → accelerate the $\bar{\mathrm{H}}$ population along z-axis to few 100m/s

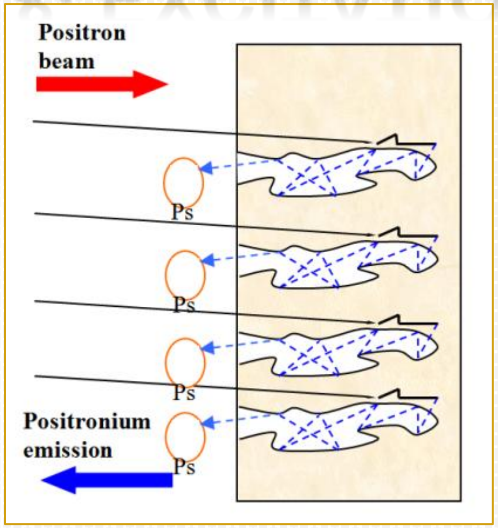
POSITRONIUM PRODUCTION & EXCITATION

- Ps production: implantation of e^+ into nano-porous (Ø 8-14 nm) silica target
- ~75K o-Ps needed
  - requires deep implantation depth → high V

up to 50% ortho-Ps conversion efficiency!



S. Mariazzi et al., *Phys. Rev. B* 81 235418 (2010)

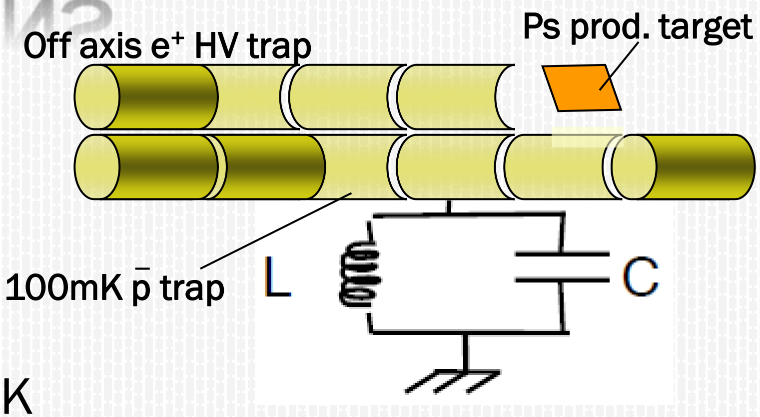


n=1 →n=3
205 nm

n=3 → n(16-30)
1650-1700 nm

- o-Ps will be excited
  - resonant 2-stage transition
  - Laser system ready
- necessary for
  - high $\bar{H}$ production rate ($\sigma \propto n^4$)
  - longer Ps lifetime

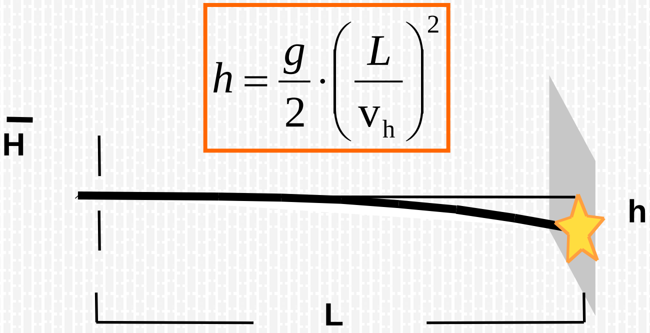
(ULTRA)COLD ANTIPROTONS



- Cold $\bar{p}$ maximize detected $\bar{H}$ flux
- Cooling in 1T $\bar{H}$ production trap
  - Currently 7K → final configuration @ 0.1K
  - Advantage: electrons stay with antiprotons
- Mechanisms to be implemented:
  - Radiative (sympathetic) e^- cooling – ideal limit 0.7K
  - To lower temperatures:
    - evaporative / adiabatic $\bar{p}$ cooling
    - sympathetic resistive cooling of antiprotons
      - e^- cooled resistively with a tuned LC circuit in a harmonic trap
  - Under investigation: sympathetic laser cooling with neg. ions (Os^-, La^-)

GRAVITY MEASUREMENT

- Horizontal antihydrogen beam @ 500m/s, flight path 1 m
  - Deflection due to gravity h = 20μm

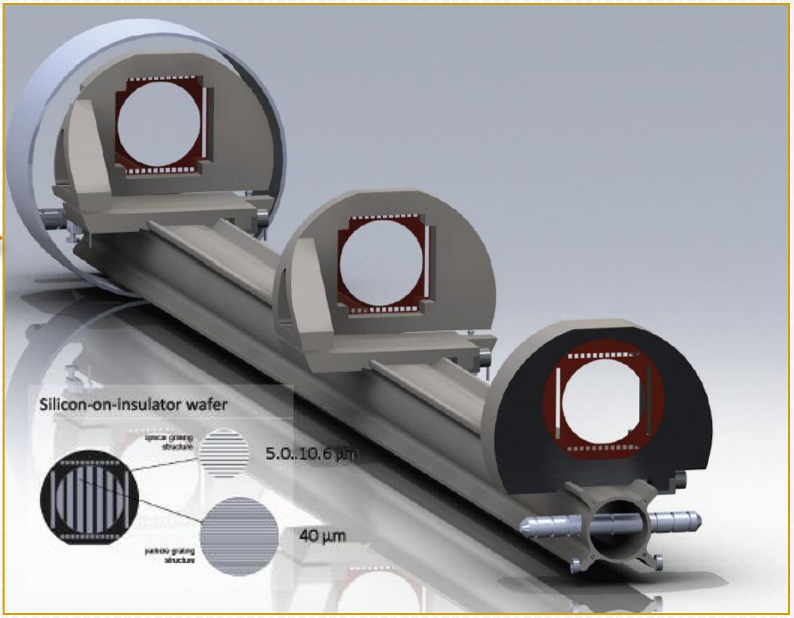


$$h = \frac{g}{2}\cdot\left(\frac{L}{\mathrm{v}_h}\right)^2$$

- AEgIS beam will have divergence ≥ 5°
  - Beam spot size after flight of the order of 20 cm
  - collimation depends on initial T($\bar{H}$)

- AEgIS will use moiré deflectometer
  - A set of horizontal gratings (40μm pitch)
  - Rel. $\delta(g)/g=10^{-4}$ achieved with Argon

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

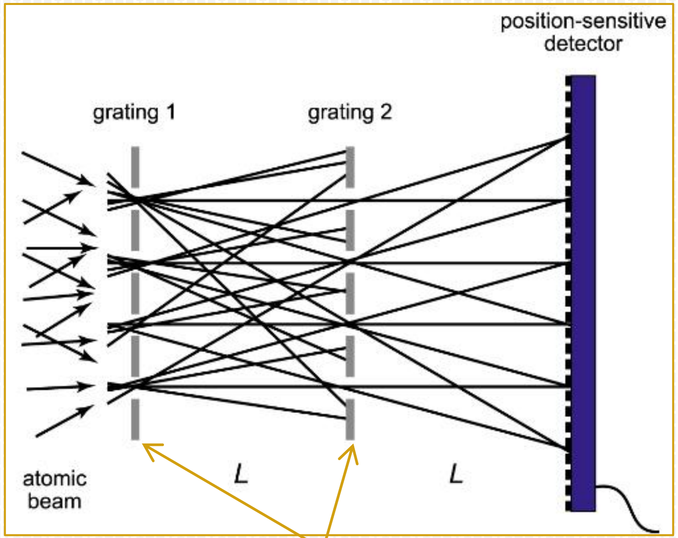


GRAVITY MEASUREMENT

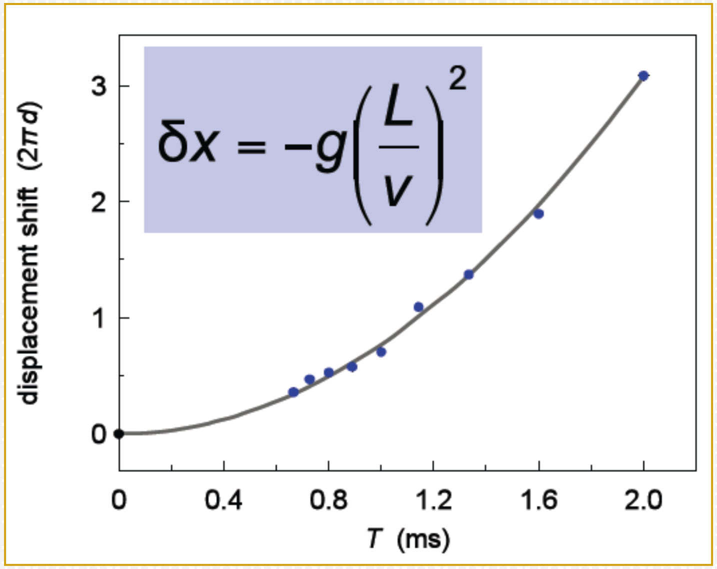
P. Bräunig's talk 16:00 today!

- moiré deflectometer
  - 2 gratings & detector
  - Classical, NOT atom interferometer
  - Collimated atom beam NOT required
  - Creates a shadow pattern
    - vertical shift δx depends on beam velocity

- In AEgIS we count position (δx) and ToF of each antiatom
  - ToF: acceleration/annihilation t
  - Flight time ~ms range
- 1% precision → ~10^3 $\overline{\mathrm{H}}$ (detected)



grating period a = 40μm (12μm slits)

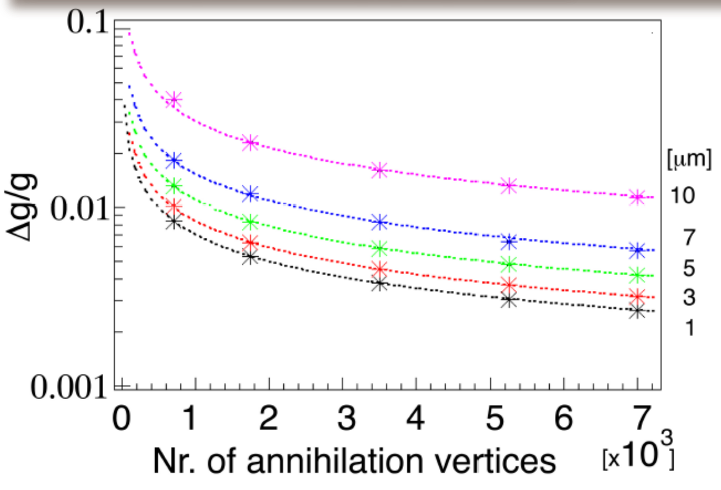


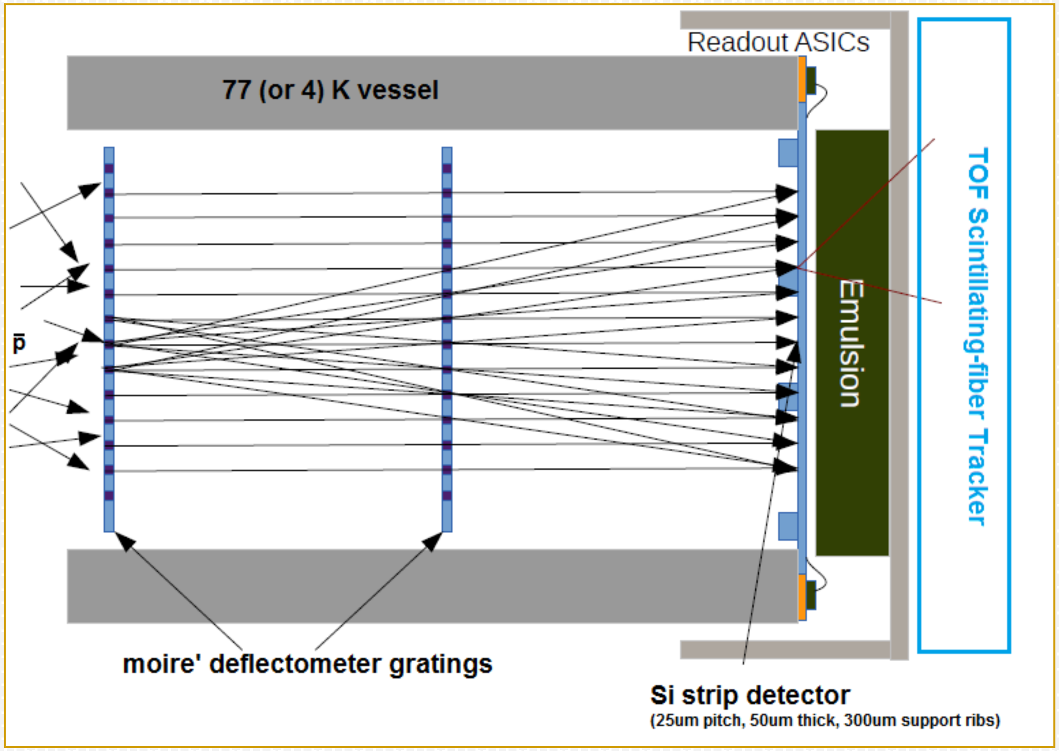
POSITION SENSITIVE DETECTOR NEW DEVELOPMENT

T. Ariga's talk 17:20 today !

- Use of nuclear emulsion
  - Superb resolution ($\sim 2\mu m$ @ $\varepsilon \approx 40\%$)
  - For $\delta(g)/g=0.01$ we need less $\overline{\mathrm{H}}$
  - Time tagging is necessary

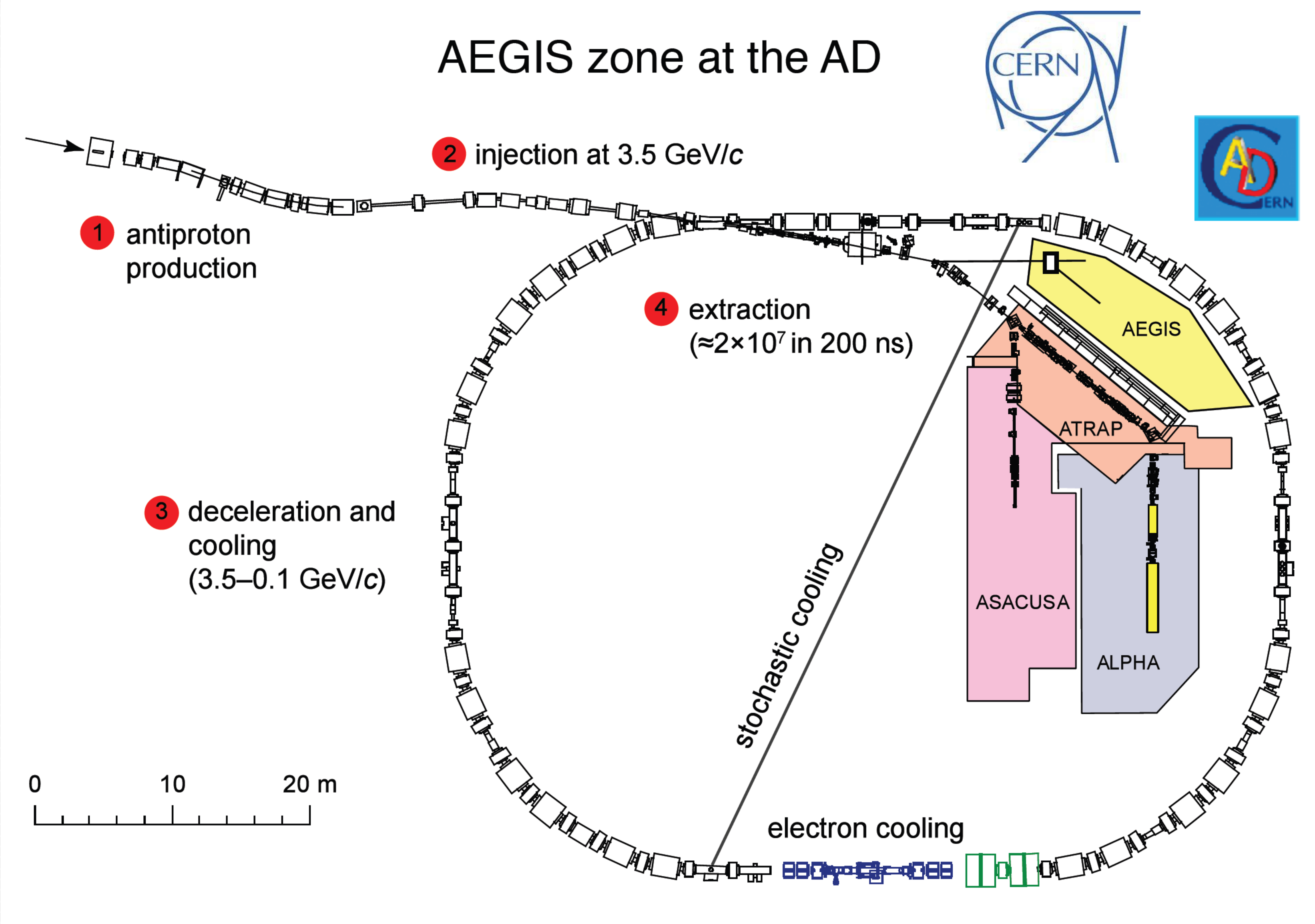
Aghion *et al.* (AEgIS), *JINST* **8** P08013 (2013)
doi:10.1088/1748-0221/8/08/P08013



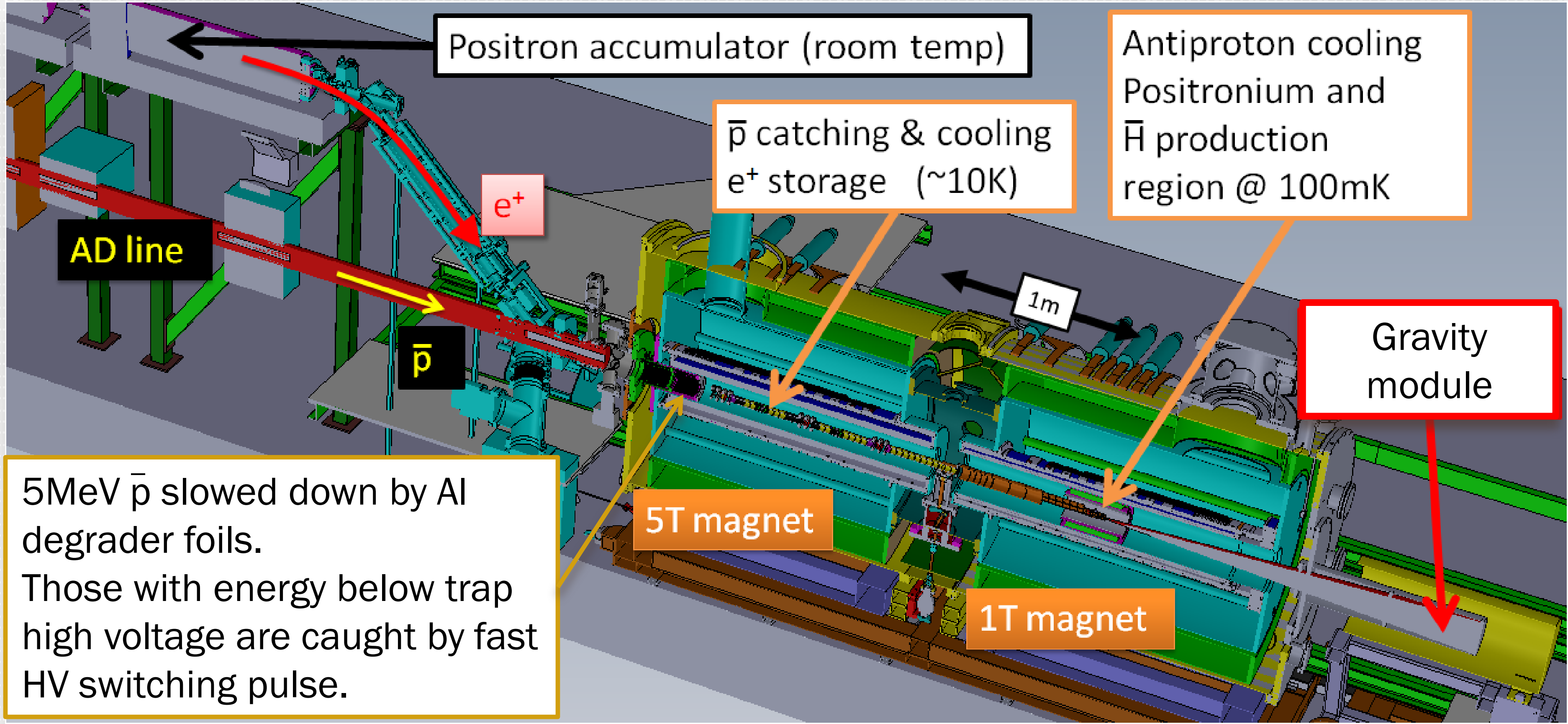


- Si detector provides:
  - Time tagging
  - vertical res. $\sigma(x) \approx 8\mu m$
  - On-line diagnostics
- TOF tracker provides:
  - "rough" x-y position, time
  - increase of efficiency

AEGIS EXPERIMENTAL APPARATUS



AEGIS EXPERIMENTAL APPARATUS



Positron accumulator (room temp)

e^+

AD line

$\bar{p}$

$\bar{p}$ catching & cooling
e^+ storage (~10K)

Antiproton cooling
Positronium and
$\bar{H}$ production
region @ 100mK

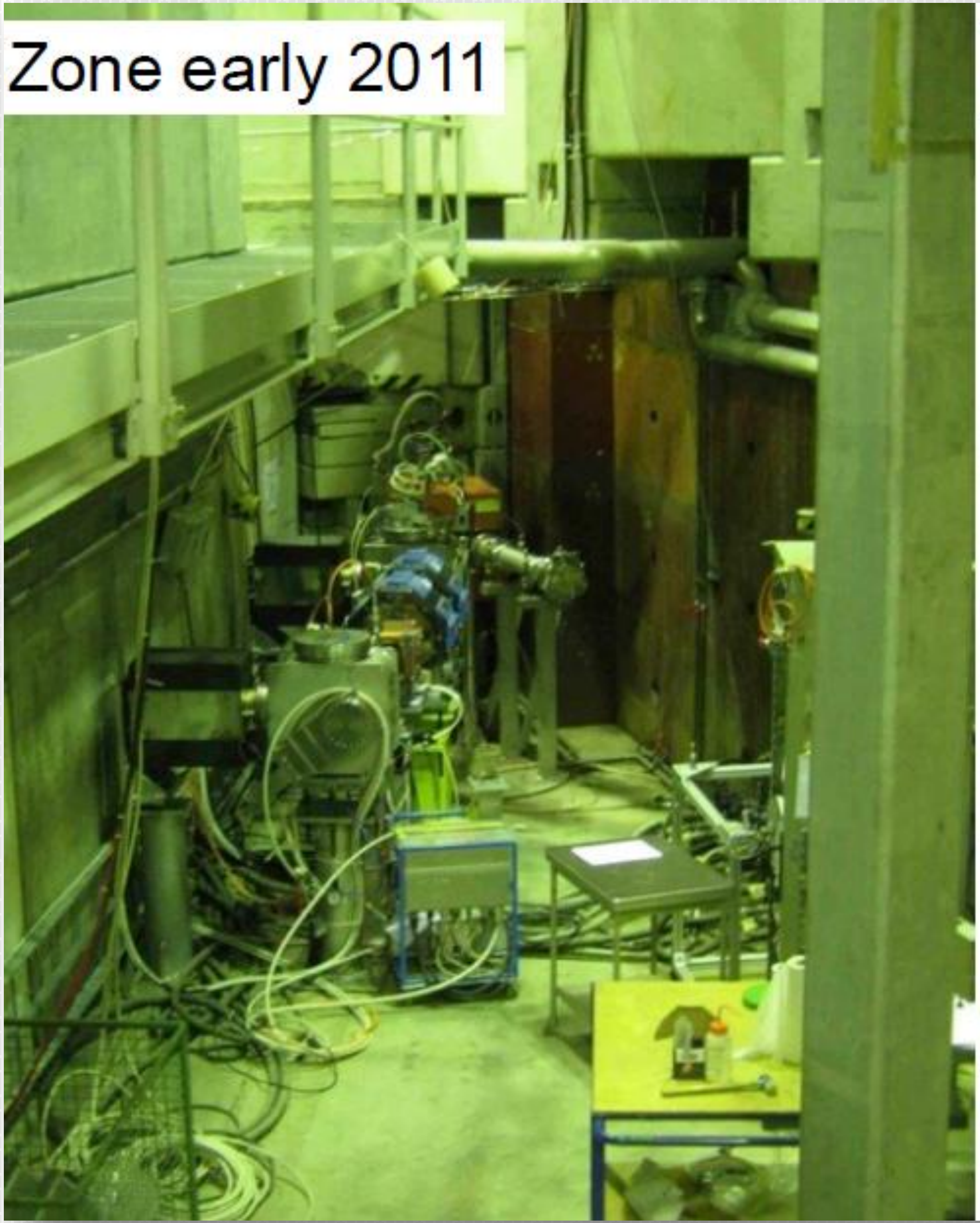
1m

Gravity module

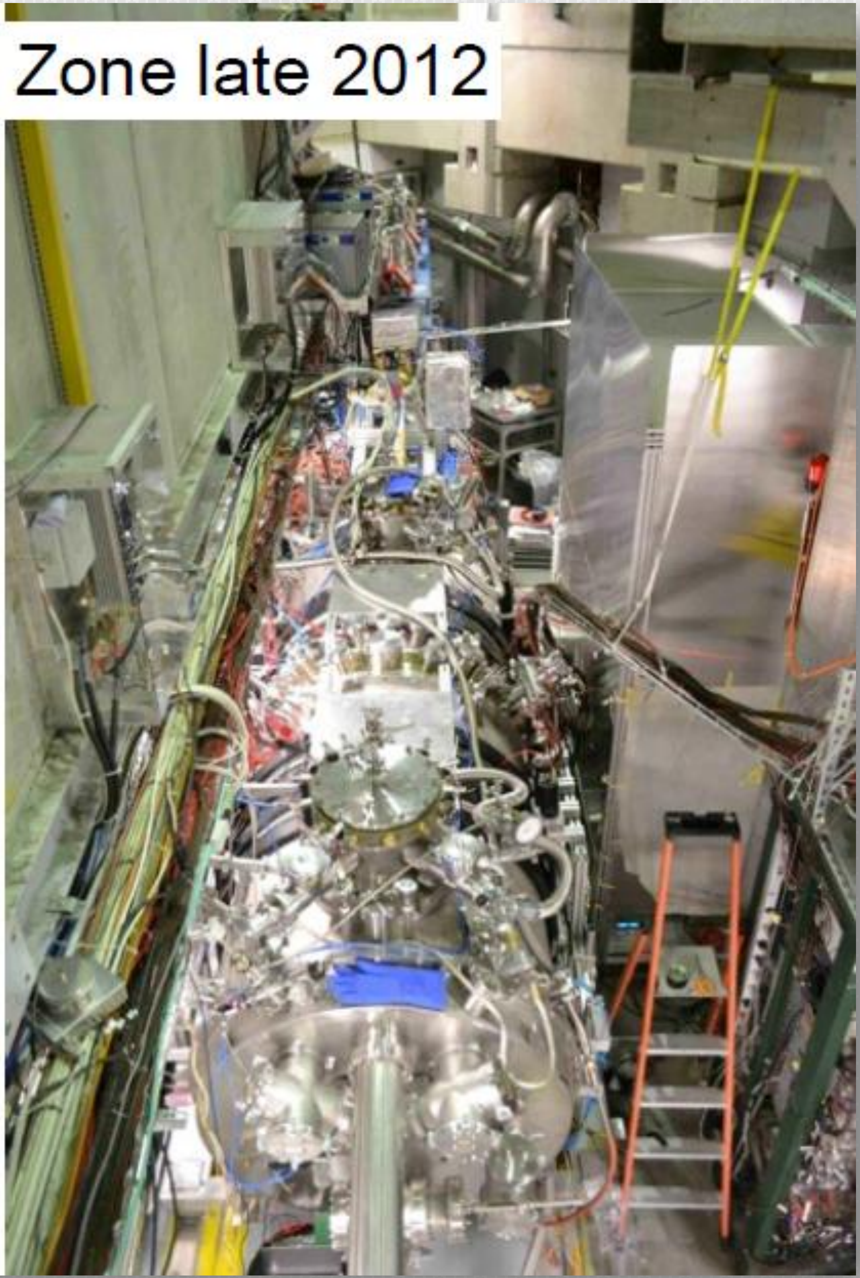
5T magnet

1T magnet

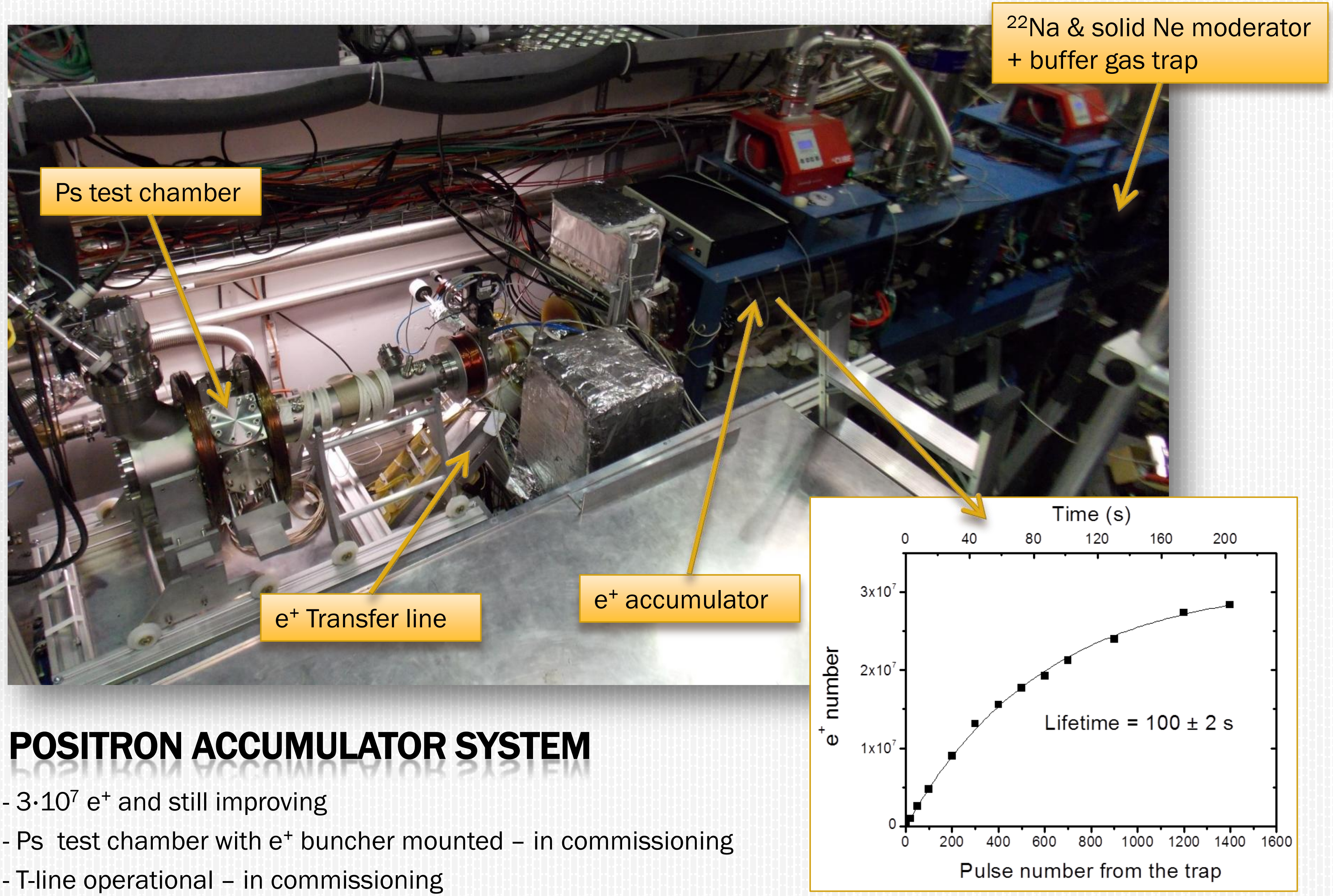
5MeV $\bar{p}$ slowed down by Al degrader foils.
Those with energy below trap high voltage are caught by fast HV switching pulse.



Zone early 2011



Zone late 2012



^{22}Na & solid Ne moderator + buffer gas trap

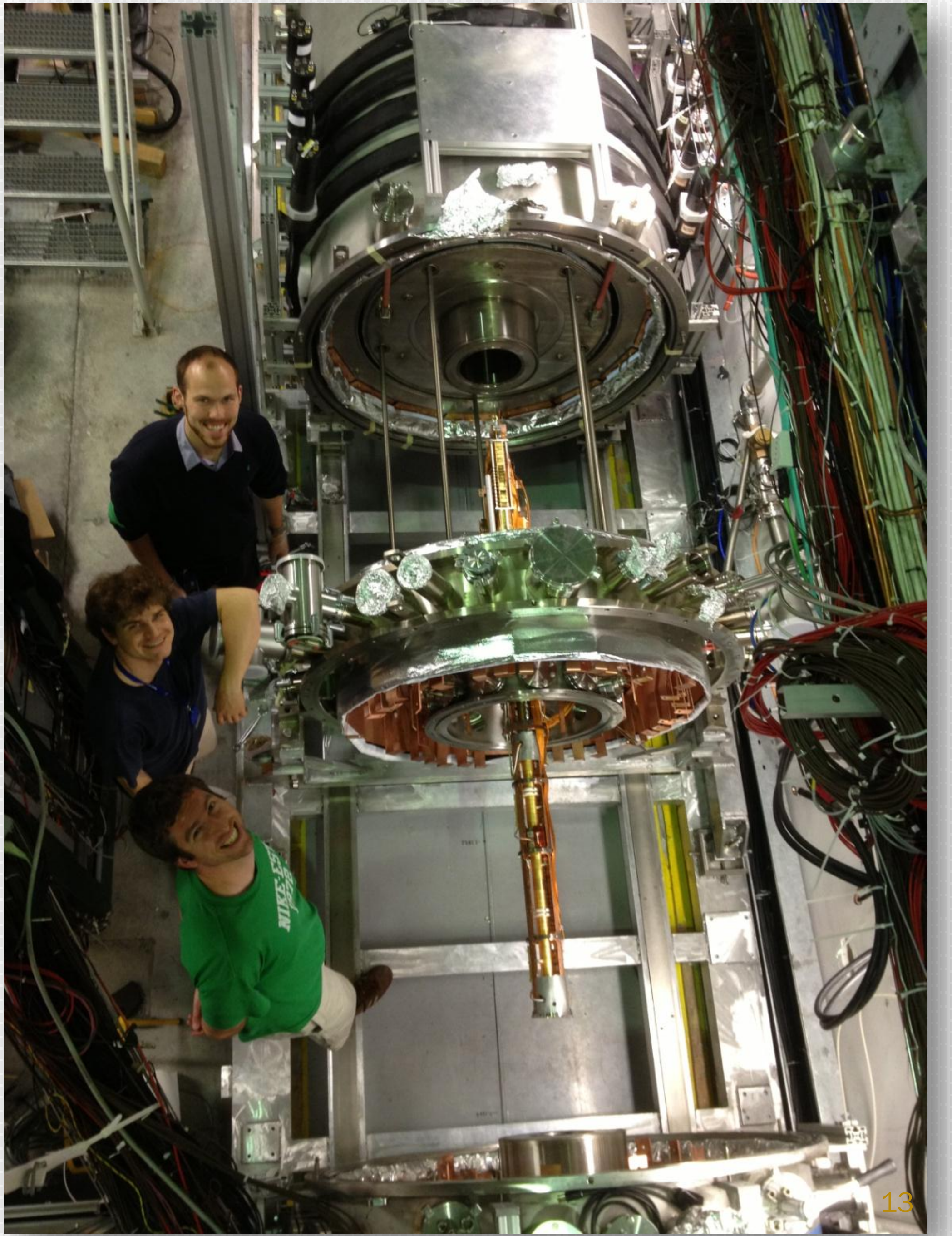
Ps test chamber

e$^+$ Transfer line

e$^+$ accumulator

POSITRON ACCUMULATOR SYSTEM

- 3·10^7 e$^+$ and still improving
- Ps test chamber with e$^+$ buncher mounted – in commissioning
- T-line operational – in commissioning

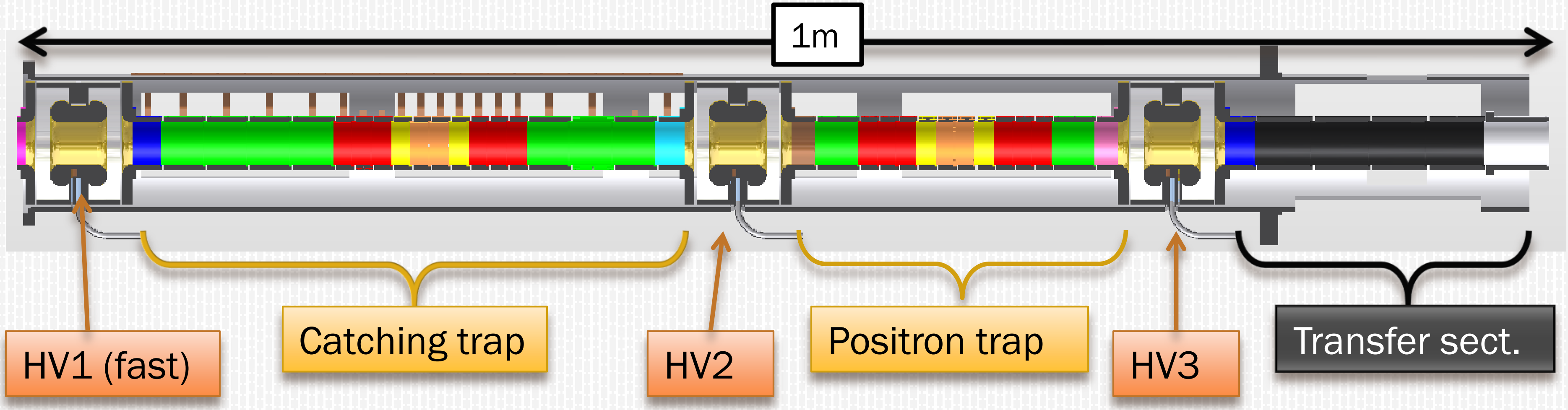


TRAP PICTURES

Left: 5 T catching trap on its support flange

Right: installation of both 1 & 5 T traps in the AEgIS magnets' cryostat

AEgIS 5T PENNING-MALMBERG CATCHING TRAP



1m

HV1 (fast)

Catching trap

HV2

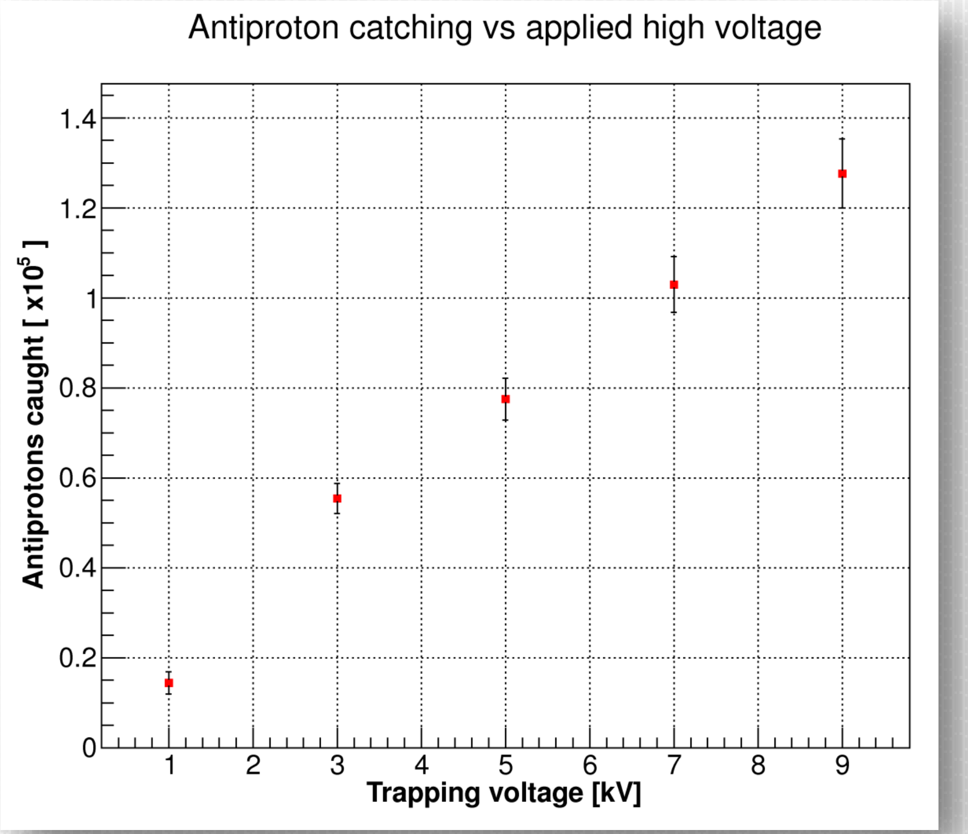
Positron trap

HV3

Transfer sect.

- Designed for $\bar{p}$ and e^+ catching, storing and subsequent transfer
- MRT, long stack of electrodes r=15mm, in 5T mag. field
- Cryogenic environment (~7K)
- Variable $\bar{p}$ catching length 46cm or 76cm
- Trap has been commissioned with antiprotons in 2012

ANTIPROTON CATCHING



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

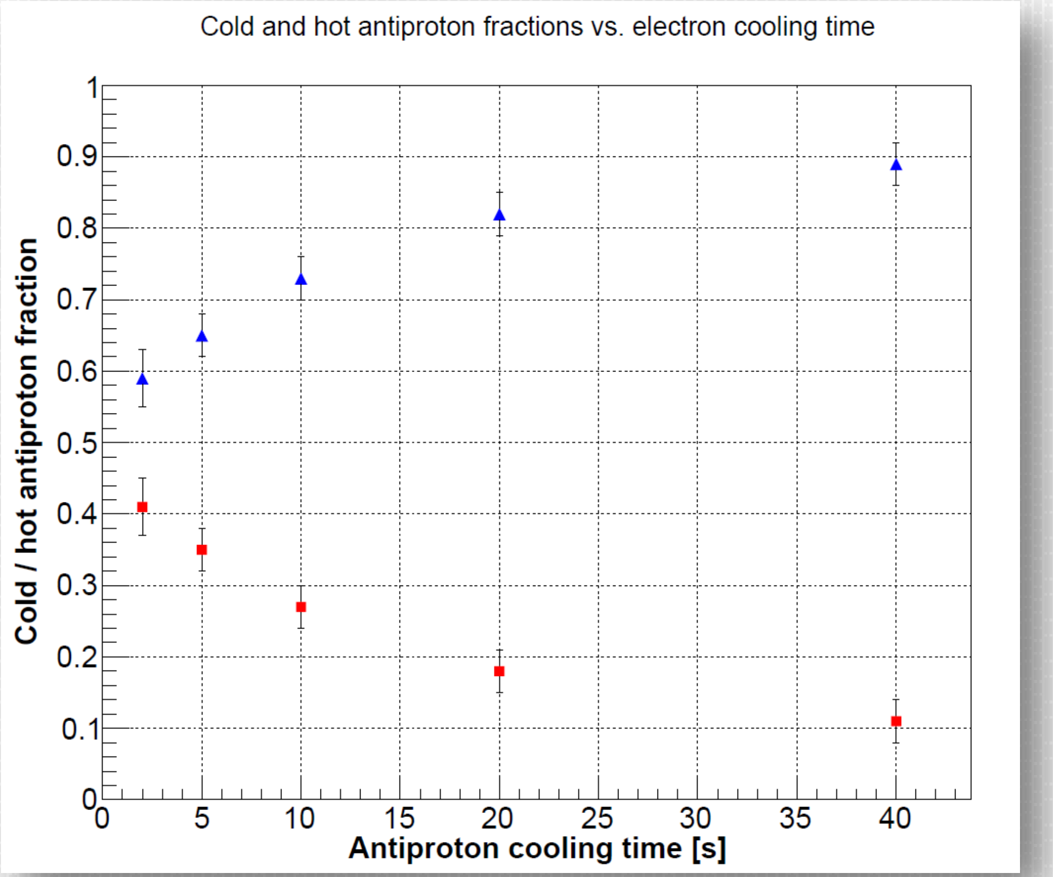
- ~$3 \cdot 10^7$ antiprotons in AD shot (@5MeV) are degraded with a set of aluminum foils.
- $\bar{p}$ with E < Trap HV are caught by fast HV on entrance electrode
- ~$1.3 \cdot 10^5$ $\bar{p}$ caught / AD shot
- Antiprotons were stored for 5s before released towards the degrader: “hot dump”
- Detection with scintillators positioned around the cryostat

ELECTRONS & COOLING OF ANTIPROTONS

- e$^-$ pre-loaded into a ~120V trap using heated cathode e-gun
  - N(e$^-$) ~10^8 -10^9
  - Electron lifetime >>100s

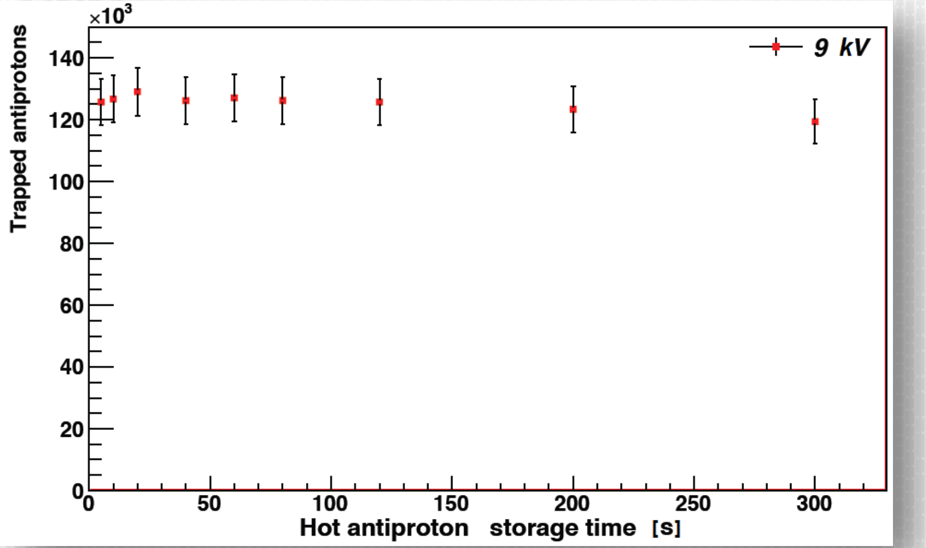
- $\bar{p}$ cool by collisions with e$^-$
  - e$^-$ cool by radiation in 5T field

- Most antiprotons are cooled within 40s from capture

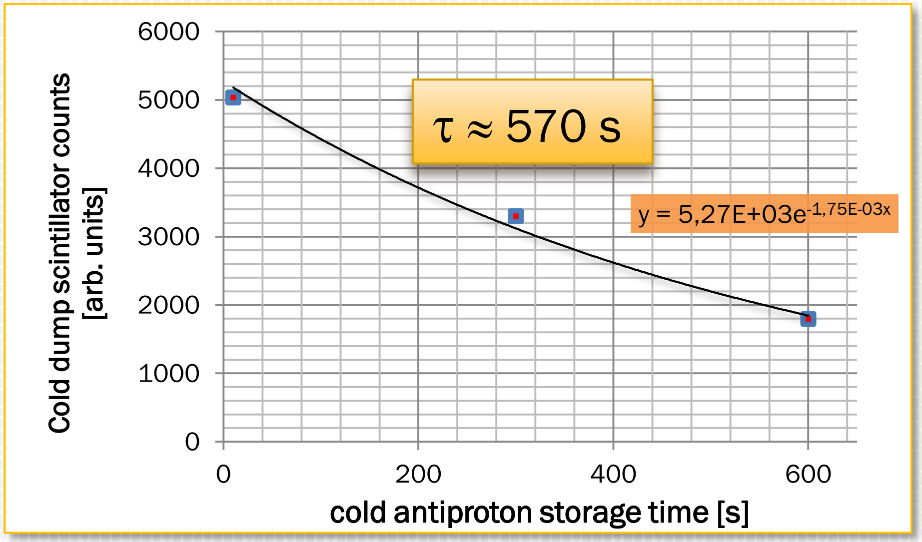

Cold and hot antiproton fractions vs. electron cooling time

ANTIPROTON STORAGE TIME

IN THE 5T CATCHING TRAP

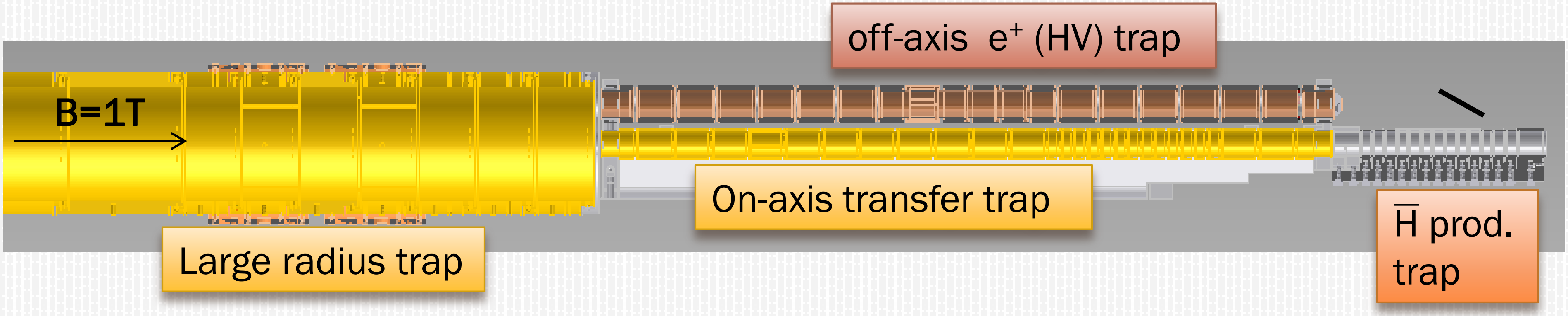


- No significant losses for hot antiprotons (46cm long trap)
  - we see similar storage behavior in the 76cm long HV trap



- Dec 2012: ~600 s lifetime of cold antiprotons
  - Oct 2013 vacuum improved by factor 2
  - lower temperature in the cryogenic region
  - we expect to increase cold pbar lifetime by a factor 2-4

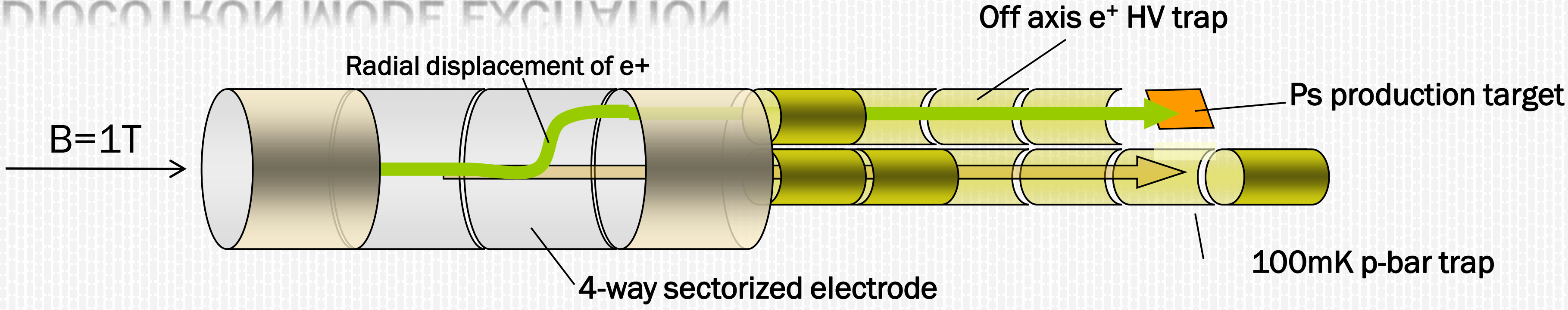
AEGIS 1T TRAP SYSTEM



- Complex system of traps with various requirements
- Large radius trap
  - plasma compression & off-axis e^+ trap loading
- Off-axis trap (working at high voltage)
  - plasma compression & acceleration of e^+ on Ps conversion target
- Antihydrogen production trap
  - final $\bar{p}$ cooling & charge exchange reaction
  - cold beam formation
- The system is currently under commissioning with e^- and e^+

MOVING POSITRONS OFF-AXIS

DIOCOTRON MODE EXCITATION



- Loading e$^+$ plasma (N≈10^8) into an off-axis trap @ 1T
  - auto-resonant excitation (pioneered by Fajans et al.) developed for e$^+$ multicell trap:

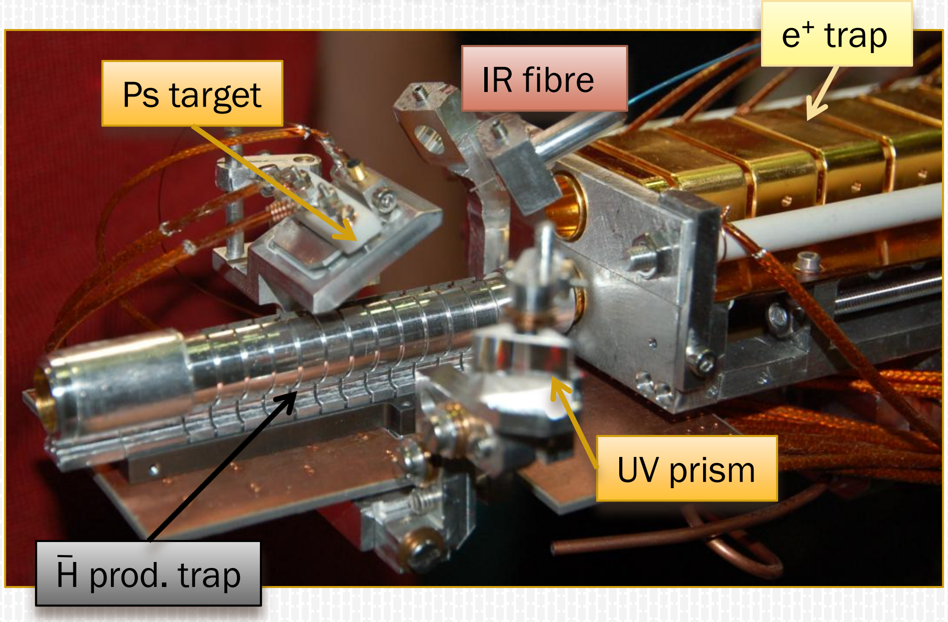
    J.R. Danielson, T.R. Weber, C.M. Surko, Phys. Plasmas **13**, 123502 (2006)

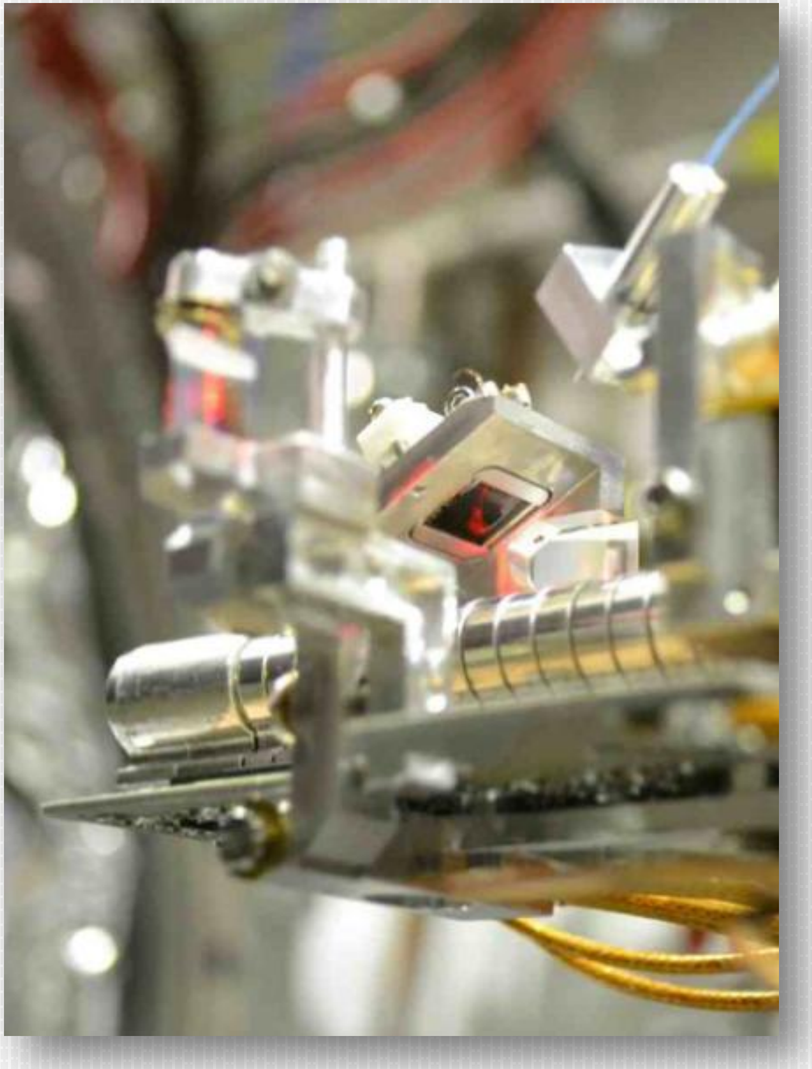
  - We successfully tested the technique with an electron trap at INFN Genova
    - low fields (0.5 – 2 T)
    - large displacements

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

  - Off-axis loading is currently under test in AEgIS 1T traps

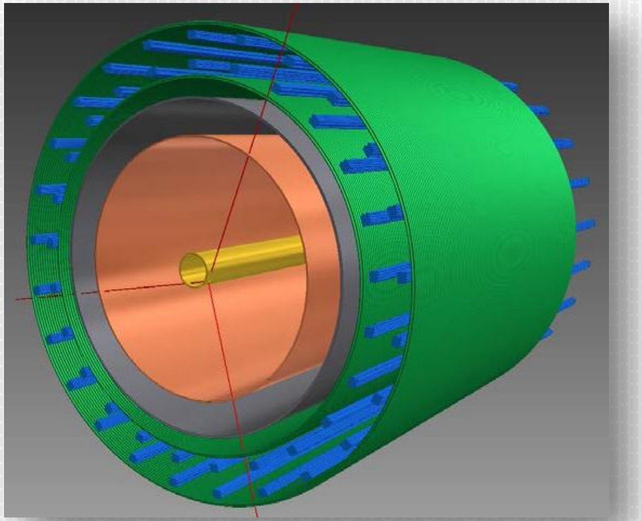
AEGIS ANTIHYDROGEN PRODUCTION TRAP



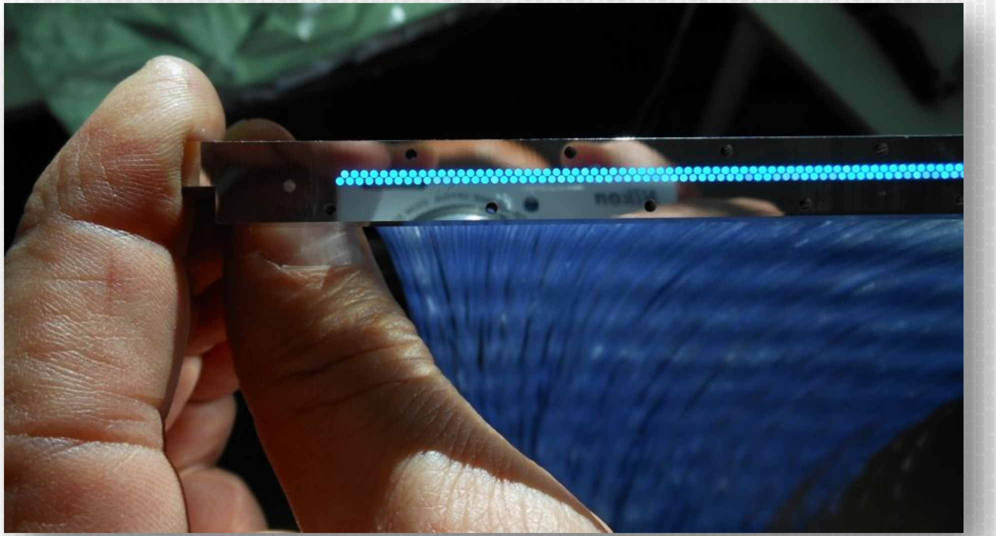


- Multi-ring Penning trap
  - single precise support structure in Al
  - support hard anodized → el insulator
  - electrodes with a fine honeycomb mesh
- Filter PCB mounted under the trap
  - by-pass diodes for fast signals included

FAST ANNIHILATION CRYOGENIC TRACKER DETECTOR



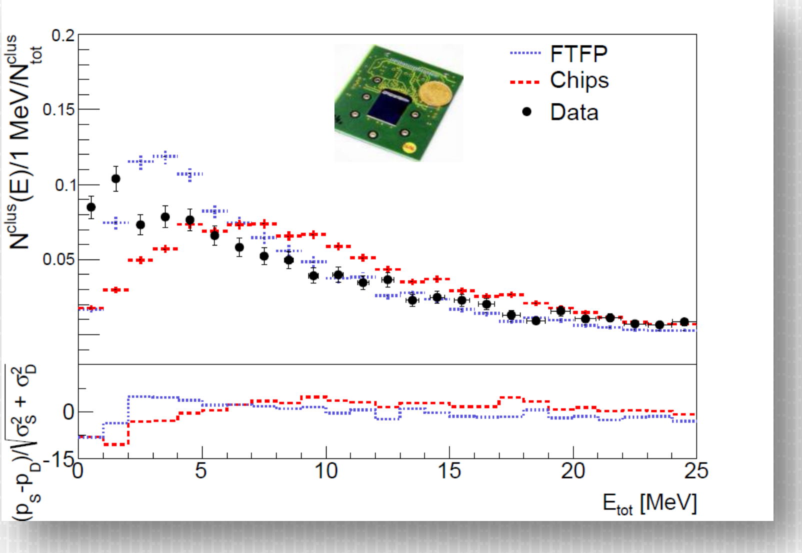
- Used to detect
  - Hbar pulsed production
  - Hbar temperature
  - Beam creation
- Fast: 50ns (Si PM response time)
- Works @ 4.2K + no heat dissipated
- expected z resolution $\sigma \approx 2.1$mm



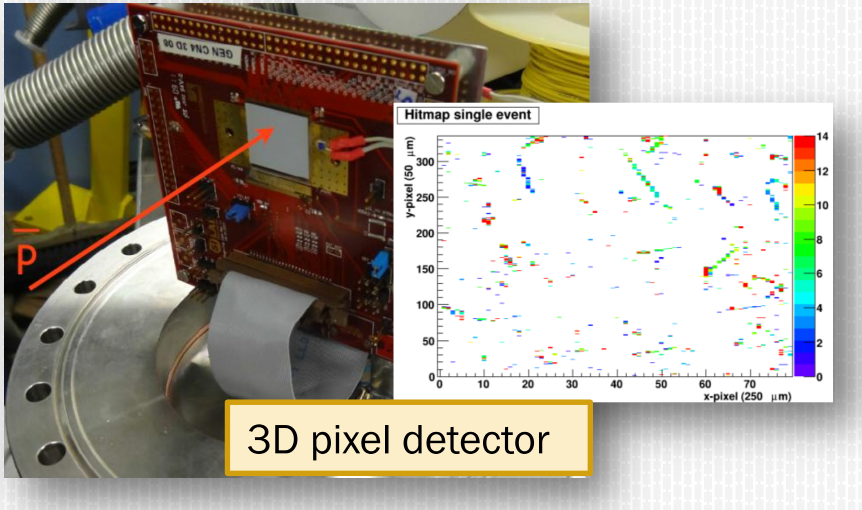
- uses 800 scintillating fibers
  - two concentric layers of fibers
  - each fiber coupled to its SiPM
- Installed and in commissioning

DETECTOR TESTS – SILICON DETECTORS

- Direct antiproton annihilation on Si sensors in vacuum
  - "Symbiotic" measurement
  - MIMOTERA pixel detector
  - Two Si strip (80 and 50μm pitch)
  - 3D Si pixel detector



- Measurements necessary for optimal gravity detector choice



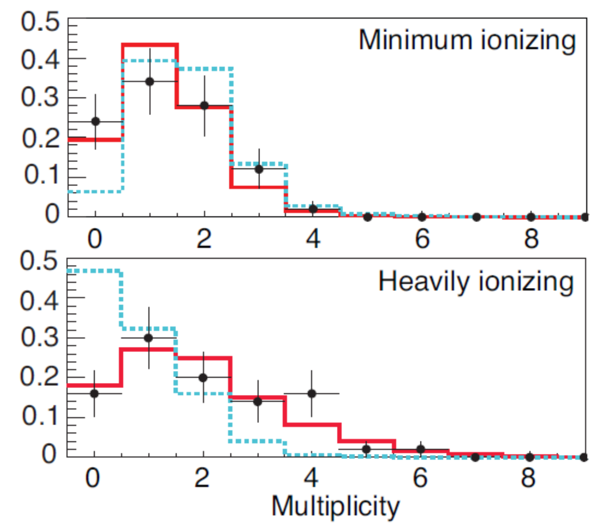
3D pixel detector

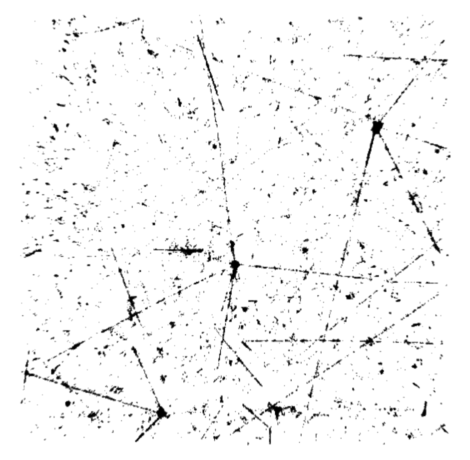
- Check of MC GEANT4
  - fair agreement
- A design of 50μm thin Si detector with 8μm resolution is feasible

DETECTOR TESTS – NUCLEAR EMULSIONS

- emulsions were tested in vacuum with low energy antiprotons
- ~2 µm position resolution expected
  - with 50µm Si detector in front
- New gel and base plate developed
  - Tests @ cryogenic temp. in progress
  - promising results!

Aghion *et al.* (AEgIS), *JINST* **8** P08013 (2013)





- GEANT4 MC comparison
  - Multiplicities: indication of better match for CHIPS rather than FTFP model
    - Positive charge is over-estimated by MC models though

SHORT TERM PLANS

- Testing of all components for $\bar{H}$ production @ 7K in 1 T field
  - Positron transport, oPs production, laser Ps excitation
  - $\bar{p}$ cooling
  - $\bar{H}$ production
  - $\bar{H}$ beam formation

- New Ps test chamber at the exit of the e^+ accumulator
  - oPs conversion efficiency @ low temperatures
  - oPs time-of-flight measurements
  - Rydberg Ps spectroscopy

- Gravity module construction (gratings, Si & emulsion detector)

- first g measurements…

AEgIS COLLABORATION

CERN, Switzerland

INFN Genova, Italy
INFN Bologna, Italy

Kirchhoff Institute of Physics,
Heidelberg, Germany

Max-Planck-Insitut für
Kernphysik Heidelberg, Germany

INFN, Università degli Studi and
Politecnico Milano, Italy

INFN Pavia-Brescia, Italy

INR Moscow, Russia

Université Claude Bernard,
Lyon, France

University of Oslo and University
of Bergen, Norway

Czech Technical University,
Prague, Czech Republic

INFN Padova-Trento, Italy

ETH Zurich, Switzerland

Laboratoire Aimé Cotton,
Orsay, France

University College, London,
United Kingdom

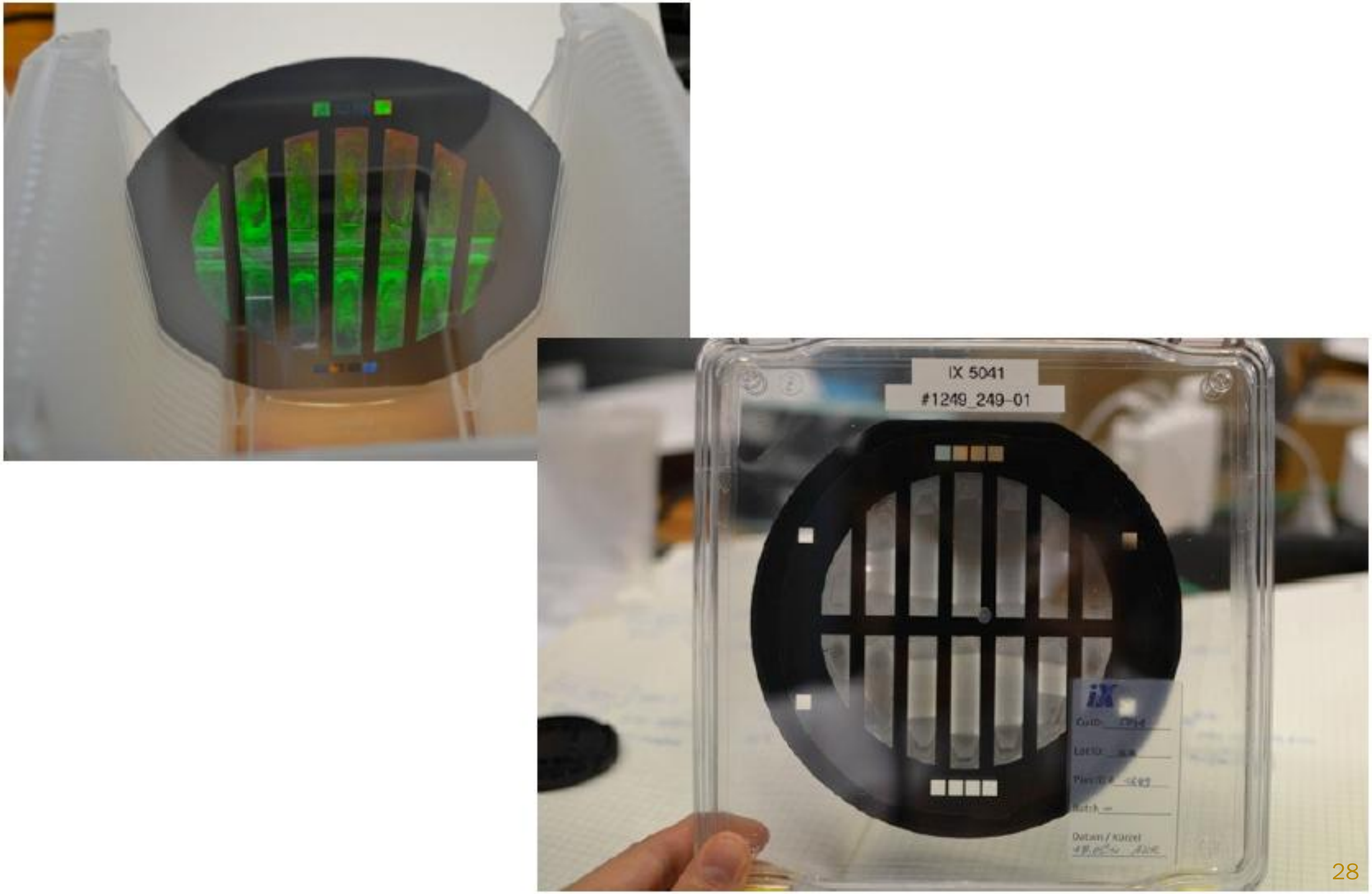
Stefan Meyer Institut,
Vienna, Austria

University of Bern, Switzerland

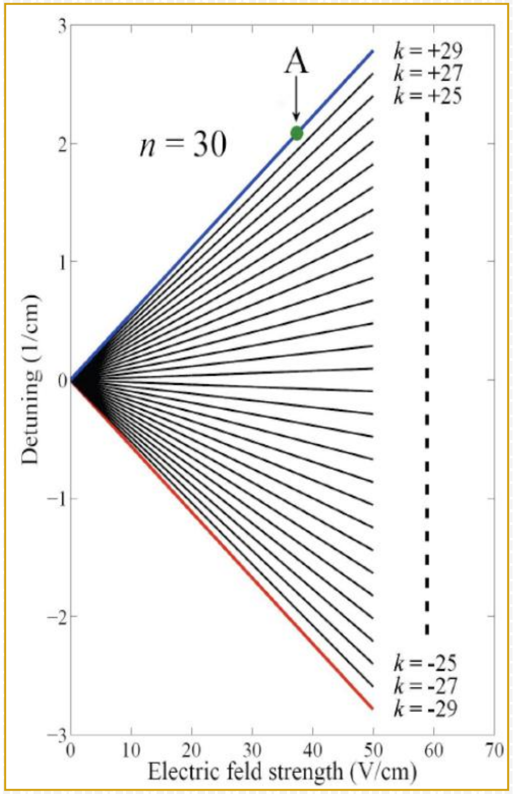
THANKS FOR YOUR ATTENTION

APPENDIX

Moiré deflectometer: 6” (full size) grating prototype



BEAM FORMATION



- Rydberg atoms have large el. dipole moment
  - Atoms are then highly sensitive to el. fields
  - accelerate/decelerate neutral (anti)matter using electric field gradients:

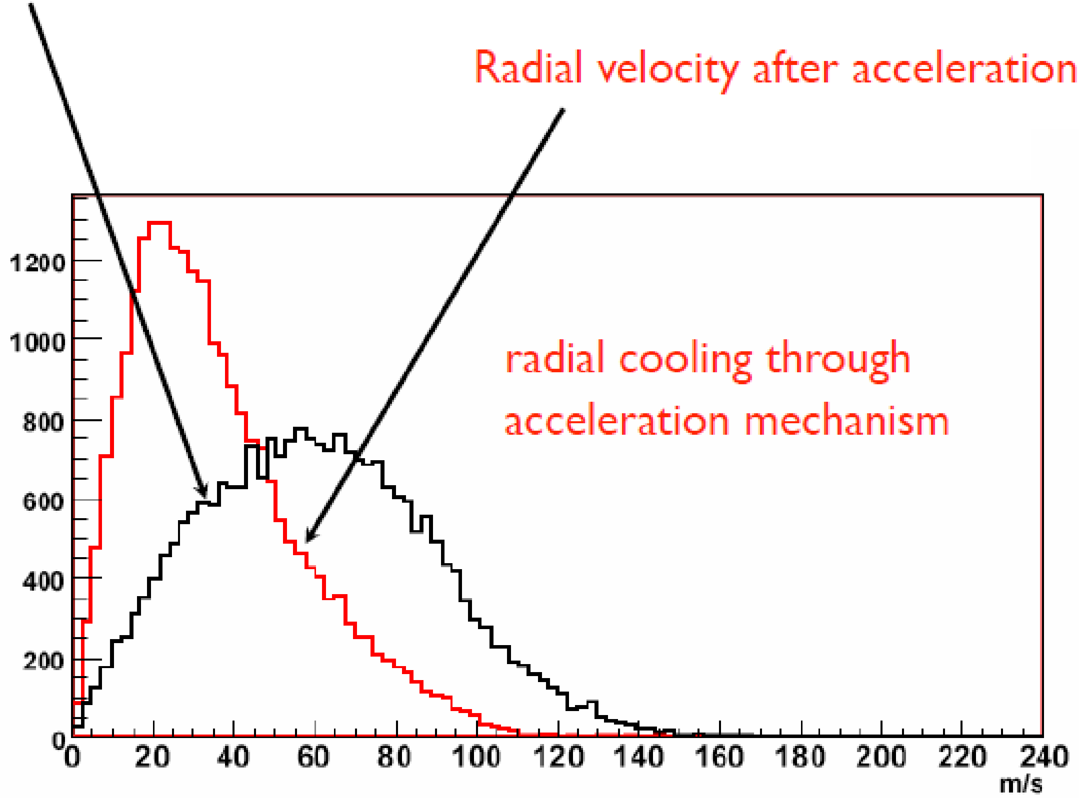
$$\vec{F} = -\frac{3}{2} e a_0 \, n(n-1) \nabla \vec{E}$$

- Deceleration of hydrogen demonstrated:
  - H @ v=700m/s stopped in 5μs over 1.8mm
  - Accelerations up to $2{\cdot}10^8$ m/s^2

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

- We will switch voltages from Penning trap configuration to “Stark accelerator”

BEAM DISTRIBUTION

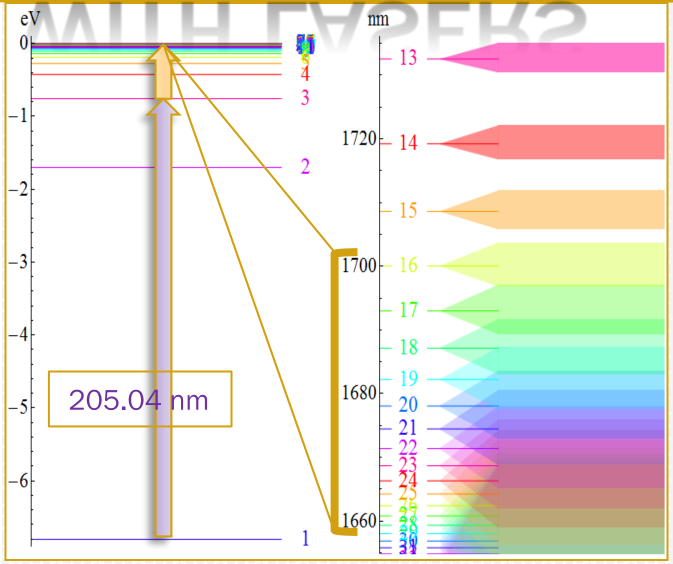


Radial velocity distribution of 400 mK antihydrogen before Stark acceleration

Radial velocity after acceleration

radial cooling through acceleration mechanism

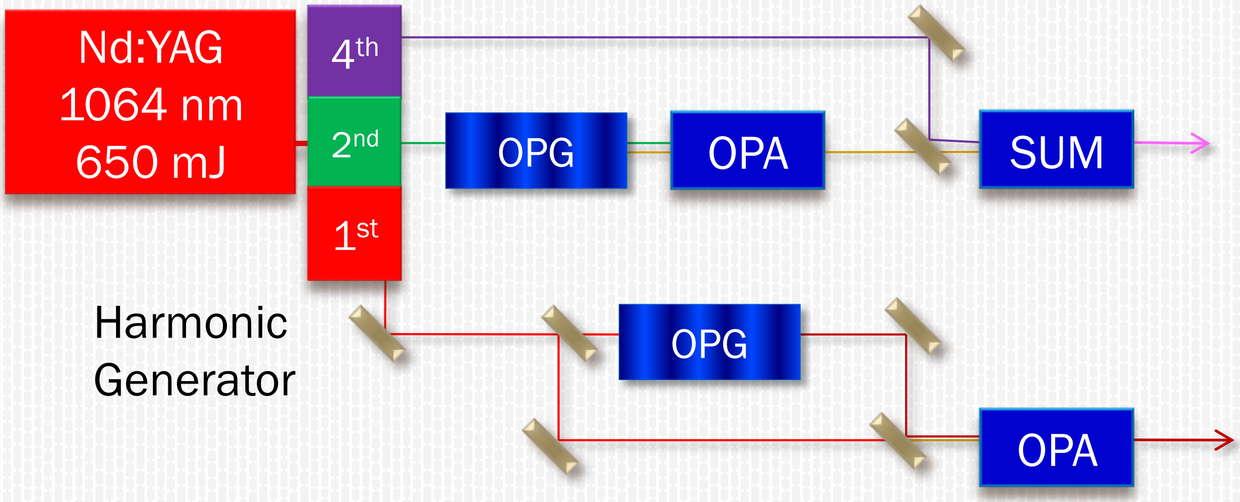
POSITRONIUM EXCITATION WITH LASERS



- o-Ps needs to be excited:
  - high $\overline{\mathrm{H}}$ production rate $\sigma \sim n^4$

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

  - Longer lifetime
- AEgIS laser system ready:
  - resonant two-stage transition



n=1 → n=3
205 nm
(300μJ available)

n=3 → n(16-30)
1650-1700 nm
(3mJ available)

POSITRON TARGET