University of Bergen

University of Brescia

CERN, Geneva

University of Genova

Heidelberg University

Max Planck Institute for Nuclear Physics, Heidelberg

University of Trento

University of Lyon

University of Milano

Politecnico di Milano

Institute of Nuclear Research of the Russian Academy of Science, Moscow

University of Oslo

Lab. Aime' Cotton Orsay

University of Pavia

Czech Technical University, Prague

INFN Sections of Genova, Milano, Padova, Pavia, Trento

Stefan Meyer Institute, Vienna

AEgIS Status Report

GEMMA TESTERA, INFN GENOVA (IT) on behalf of the AEgIS Collaboration

CERN, SPSC Meeting - January 2018

AEgIS (Antimatter Experiment Gravity Intereferometry Spectroscopy) goals

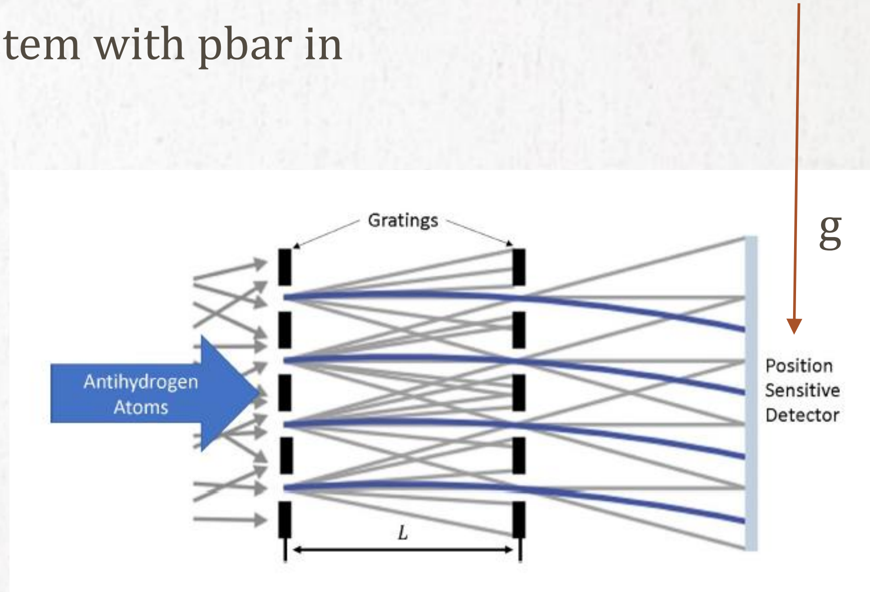
Test the validity of fundamental principles with antihydrogen : **WEP – CPT**

- **g measurement on anti-H**:

vertical shift of a cold beam travelling through a grating system coupled with a position sensitive detector (classical deflectometer or interferometer)

Proof of principle of tiny vertical force measurement with the grating system with pbar in

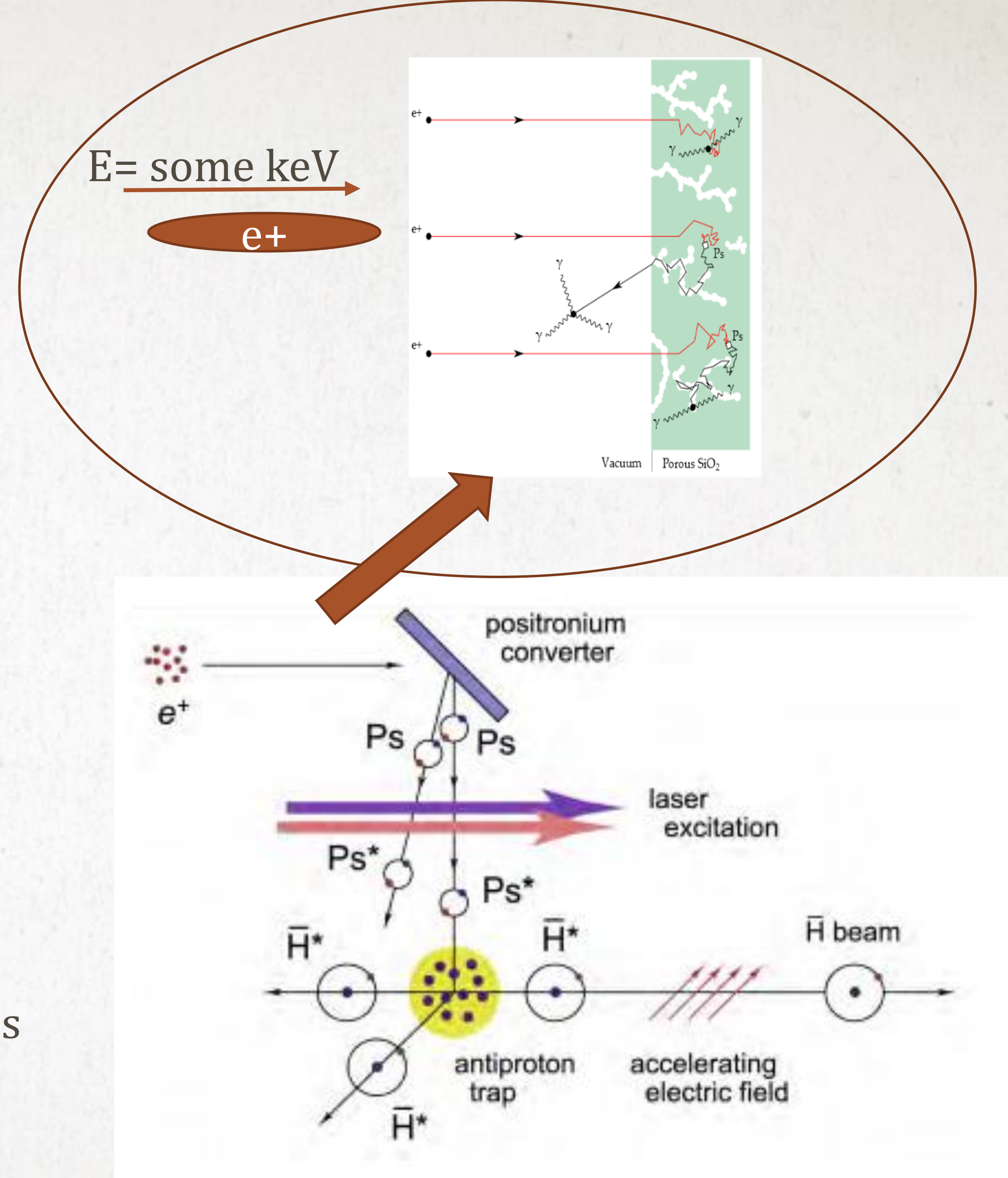
AEgIS Coll, Nature Comm. 5, 4538 (2014) A moire' deflectometer for antimatter



- **Hbar spectroscopy with a cold beam: HFS**

AEgIS Methods

- cold pulsed antihydrogen beam
- Antihydrogen formation through $\overline{p} + Ps^{*} \rightarrow \overline{H}^{*} + e^{-}$
- Ps formation via impact of e+ on converter material
- Ps laser excitation to Rydberg states
- Ps interaction with pbar previously stored close to the target
- Hbar formation in Rydberg states
- Beam formation: Hbar acceleration with suitable electric fields



2017 run: First antihydrogen formation trials

Commissioning of all the necessary subsystems

- Antiprotons
- Ps formation
- Laser and Ps laser excitation
- antiH detectors (FACT)

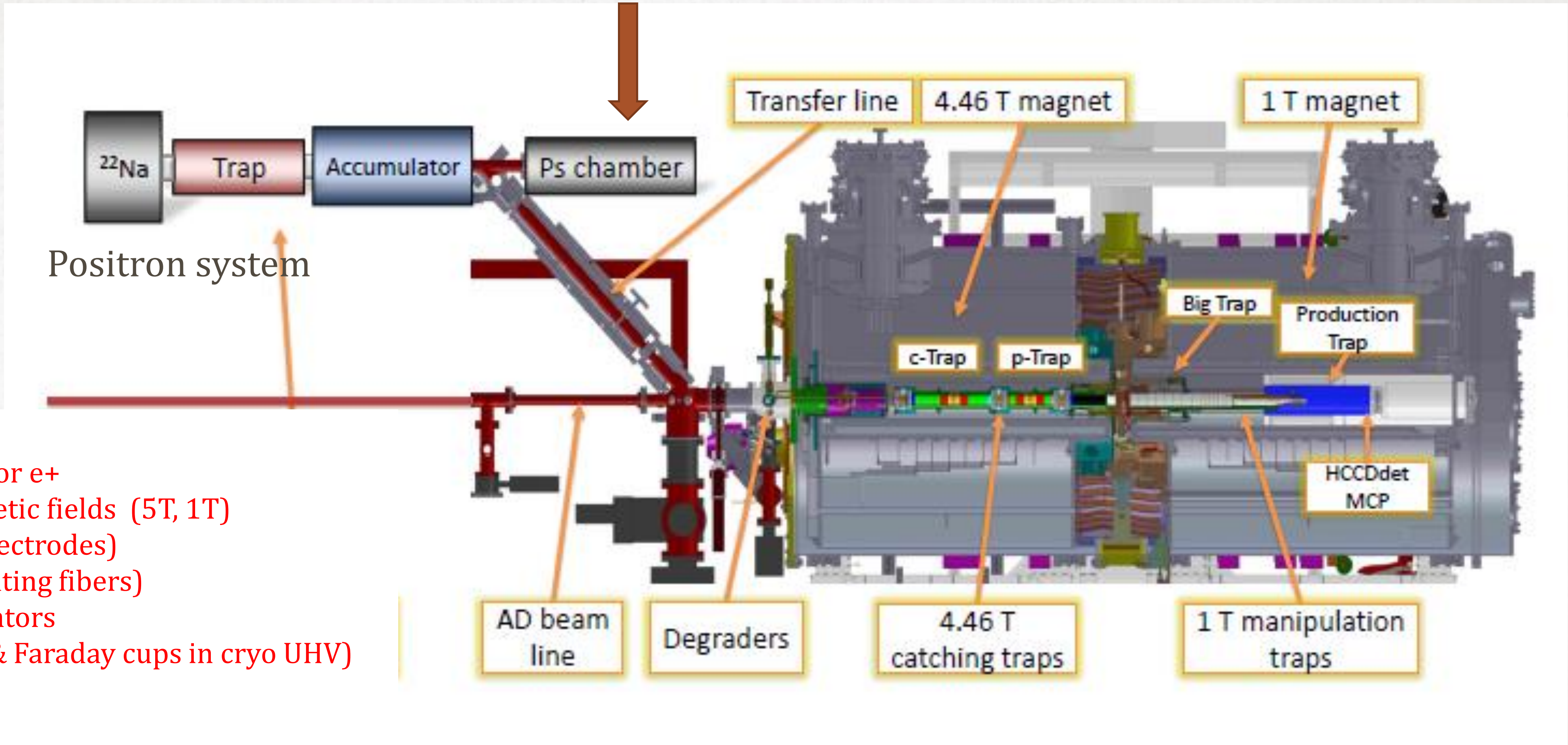
AegIS apparatus

Ps test setup

used for the first Rydberg Ps excitation as planned during Hbar formation

"Laser excitation of the n=3 level of positronium for antihydrogen production"

Phys. Rev. A 94 (2016) 012507 AEgIS Coll.



- Accumulator for e+
- Magnetic transfer line for e+
- Superconducting magnetic fields (5T, 1T)
- Cryogenic traps (105 electrodes)
- antiH detector (scintillating fibers)
- External plastic scintillators
- Internal (MCP+phosp.& Faraday cups in cryo UHV)
- lasers
- Additional detectors
- POSITRON MEASUREMENT setup

Detectors

- External plastic scintillators+PMT : counting mode (pbar annihilation)
- analog waveform (pbar, e+, Ps detection)

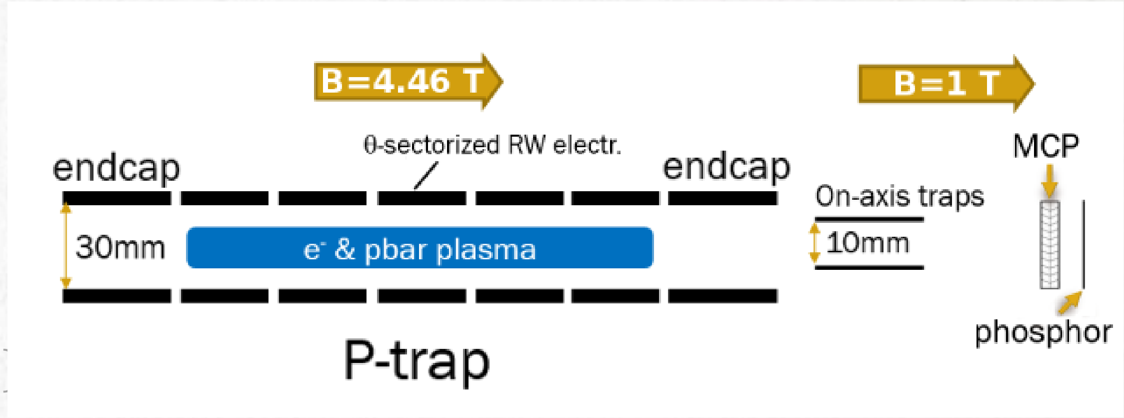
- Charge collection on Faraday cups

- Plasma Imaging system: MCP+Phosposr+ CMOS camera

Located dowstream in the 1 T region@10K

- + additional detectors (CsI, scintillators,charge pickup…)

- +Antihydrogen detector (FACT)



Trapped plasma released on MCP
Particles follow field line
Image of plasma trapped in 5T or in 1T
Plasma density z integrated

Antiproton preparation: the non standard design of the Hbar production trap ……………

- Small radius (5 mm) (mechanics not easy)
- Grid on top to allow Ps to go through
- Break of rotational symmetry

→ Asymmetries drive the radial transport of trapped plasma

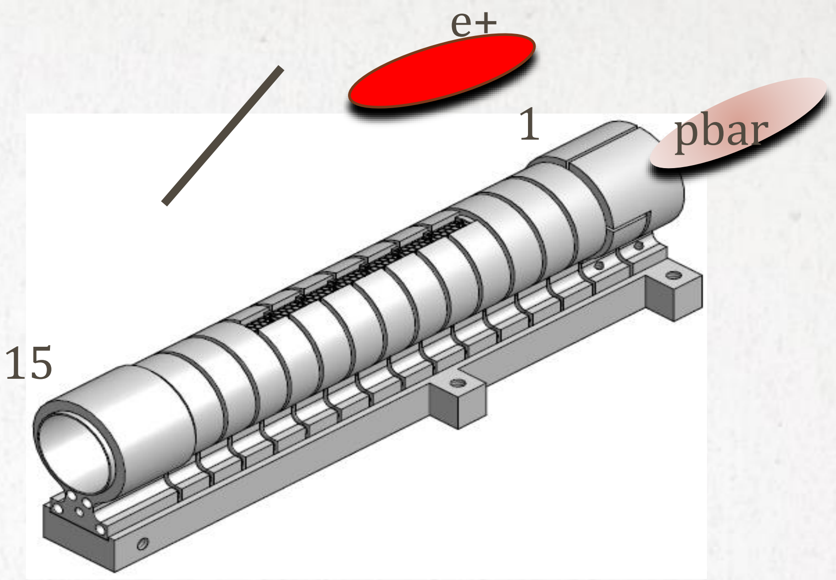
- Losses of plasma (good vacuum) are due to radial transport
- Observed plasma radial transport & expansion

(depending on the trap region, lenght, plasma density)

- Not trivial scaling law

- **Critical items**
  density control
  plasma well centered and with small radius

Electrons and antiprotons here transported from 5 T region



15 electrodes,
1 Tesla
10-20 K
r= 5 mm
L= 12 cm

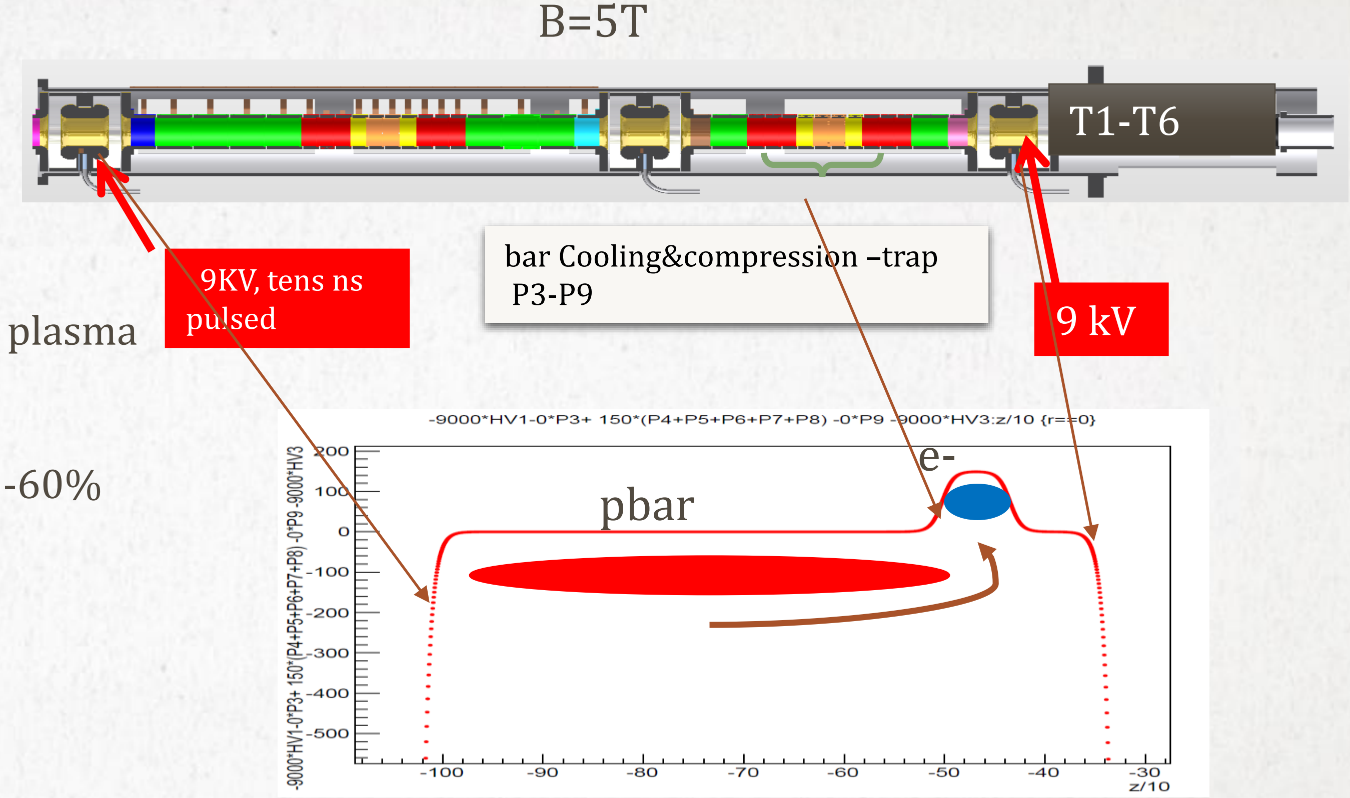
Antiprotons: trap&cool and compress in 5 T region

- 4 10^5 antiprotons/AD shot
- Slow release from the trap
- Counts detecting pions with external scintillators (counting mode)

Cooling by collision with e-: more than 90% efficiency

- Need radial compression of mixed antiprotons-electron plasma
- Necessary to transfer in the Hbar formation trap@1T

- Cool & compression (using Rotating Wall)efficiency: 50-60%



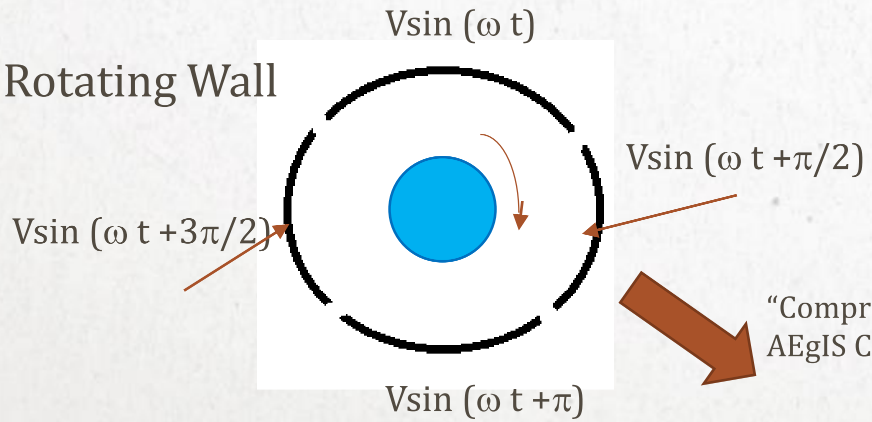
B=5T

T1-T6

9KV, tens ns pulsed

bar Cooling&compression –trap P3-P9

9 kV



Rotating Wall

Vsin (ω t)

Vsin (ω t +π/2)

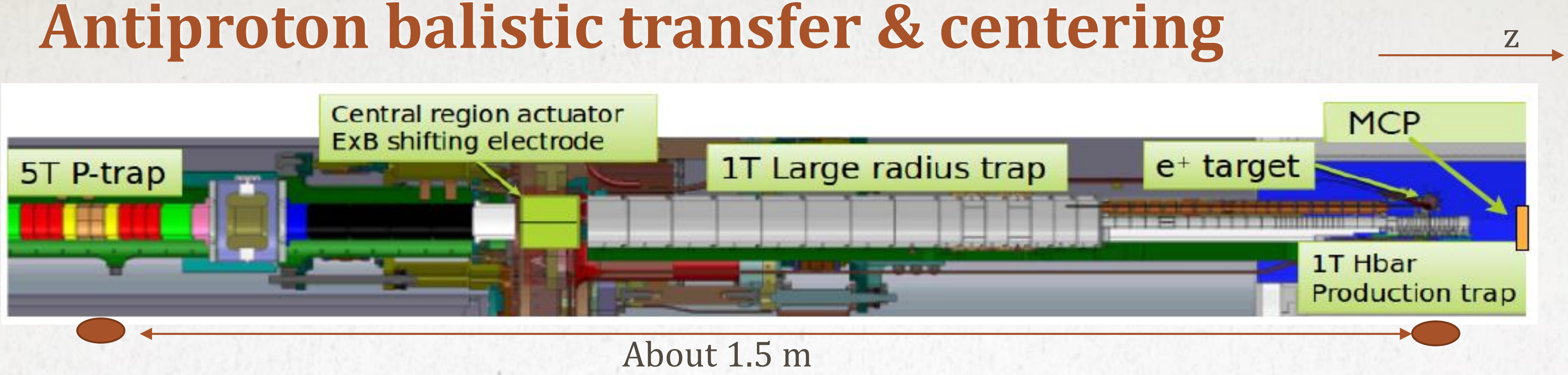
Vsin (ω t +3π/2)

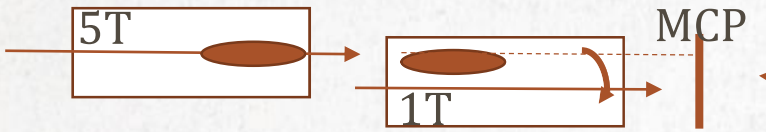
Vsin (ω t +π)

“Compression of mixed antiproton and electron plasma to high densities"
AEgIS Coll. Submitted to EPJ, first interaction with ref. complete

2 10^5 pbar/shot, radius reduced by a factor 10
r=0.17 mm n=10^7/cm^3

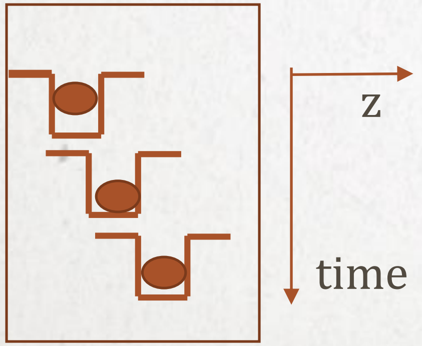
Antiproton balistic transfer & centering



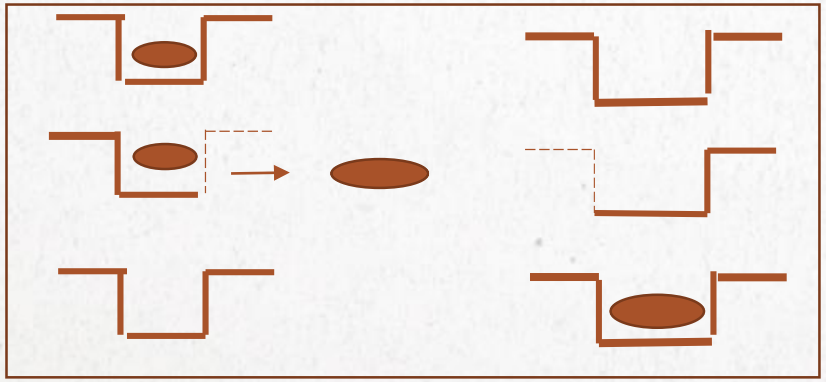


- Transfer in decreasing B: expansion
- Imperfect alignement between 5T and 1T
- Path: about 1.5 m
- Adiabatic vs balistic transfer

- Balistic transfer with trajectory correction on flight
- transfer&recatch efficiency > 90%
- EXB with shifting electrode
- Compensate imperfect alignement for pbar

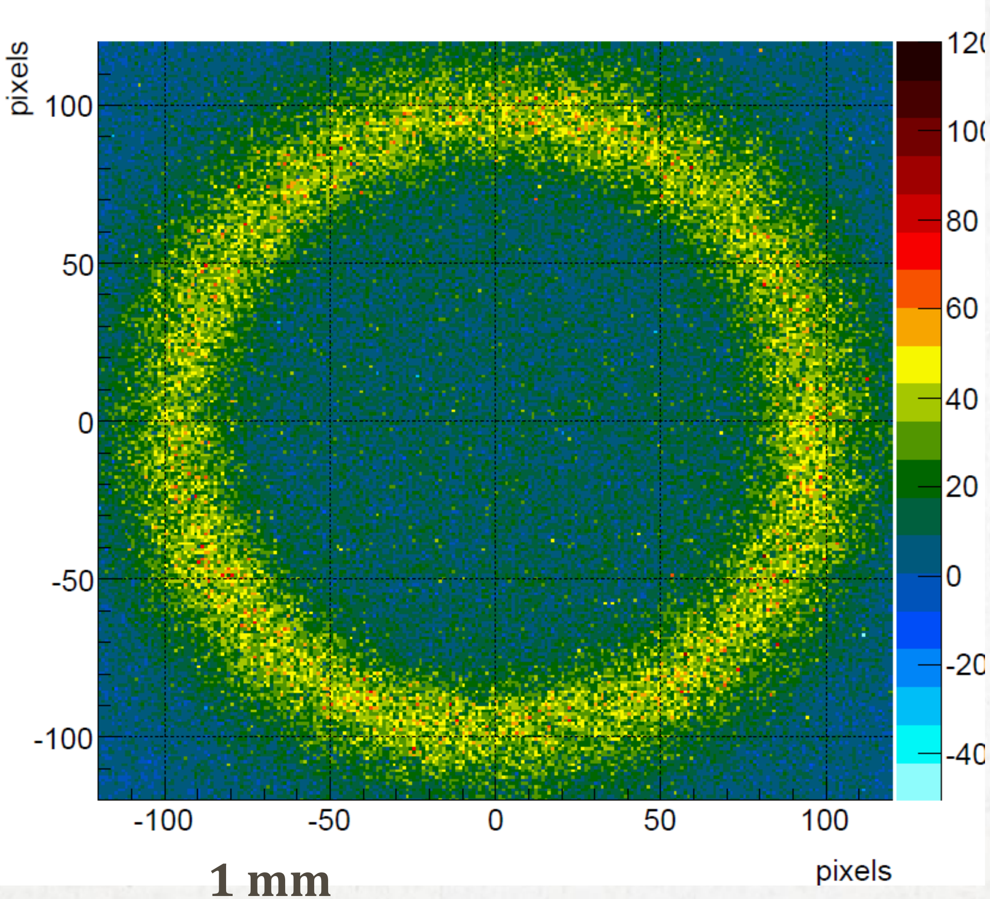


Adiabatic transfer



Balistic transfer

Antiprotons balistically transferred in the 1T trap, stored for few ms and then released on MCP



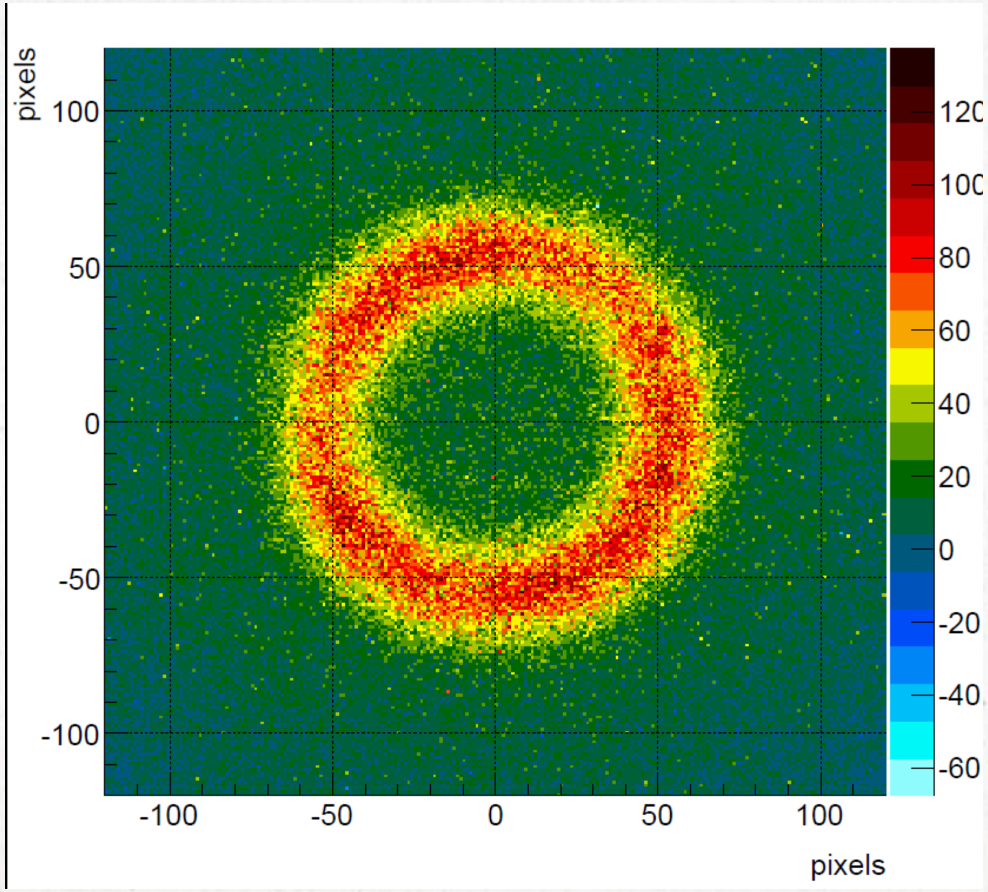
1 mm

No correction of the trajectory with the shifting electrodes

About 2 mm shift

Trap radius: 5 mm
(215 pixels)

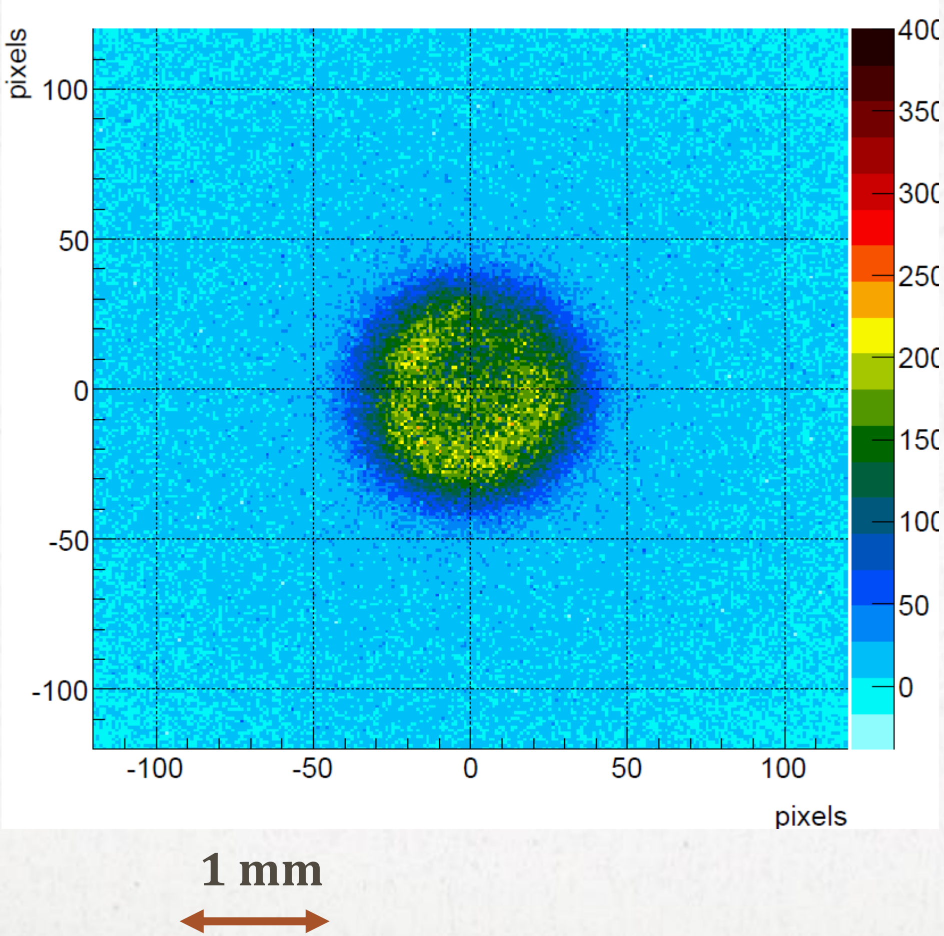
Antiprotons balistically transferred in the 1T trap, stored for few ms and then released on MCP



1 mm

Partial correction of the trajectory with the shifting electrodes

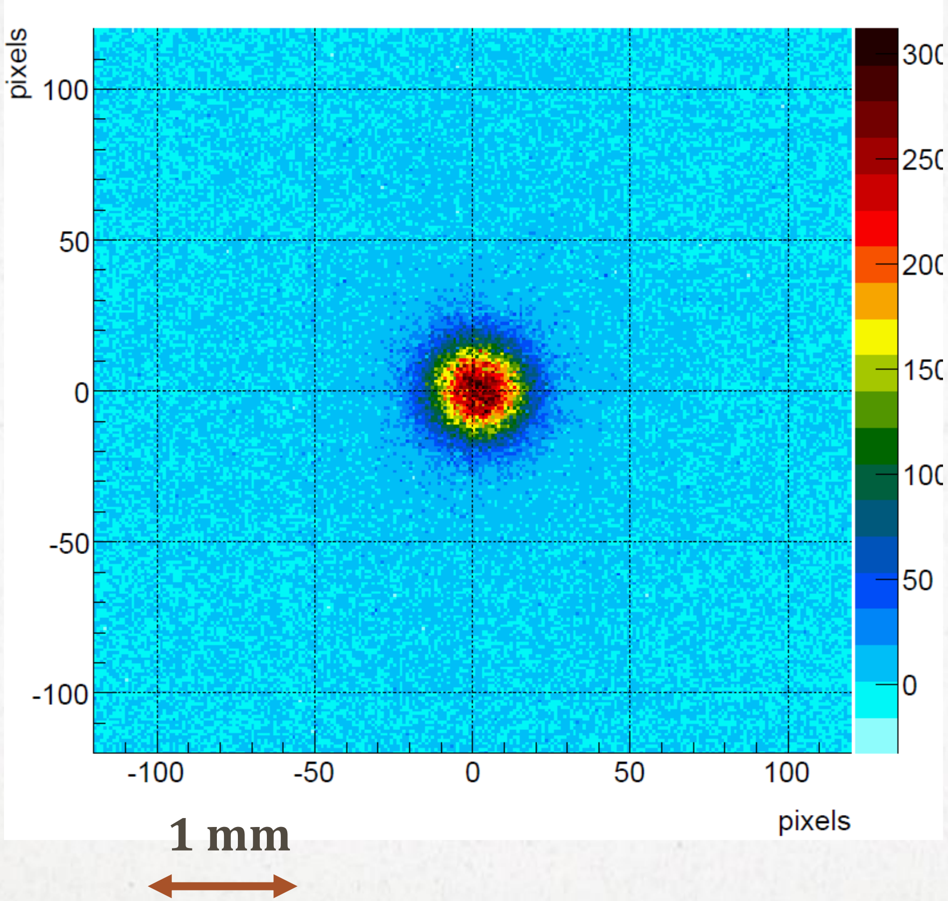
Antiprotons balistically transferred in the 1T trap, stored for few ms and then released on MCP



Use in 2017 of the optimal parameter of the correction found in 2016

Alignement changed during the opening and closing of the vacuum chamber

Antiprotons balistically transferred in the 1T trap, stored for few ms and then released on MCP



Optimal setup of the shifting electrode in 2017

Plasma size only increases because of the lower field

No initial additional expansion

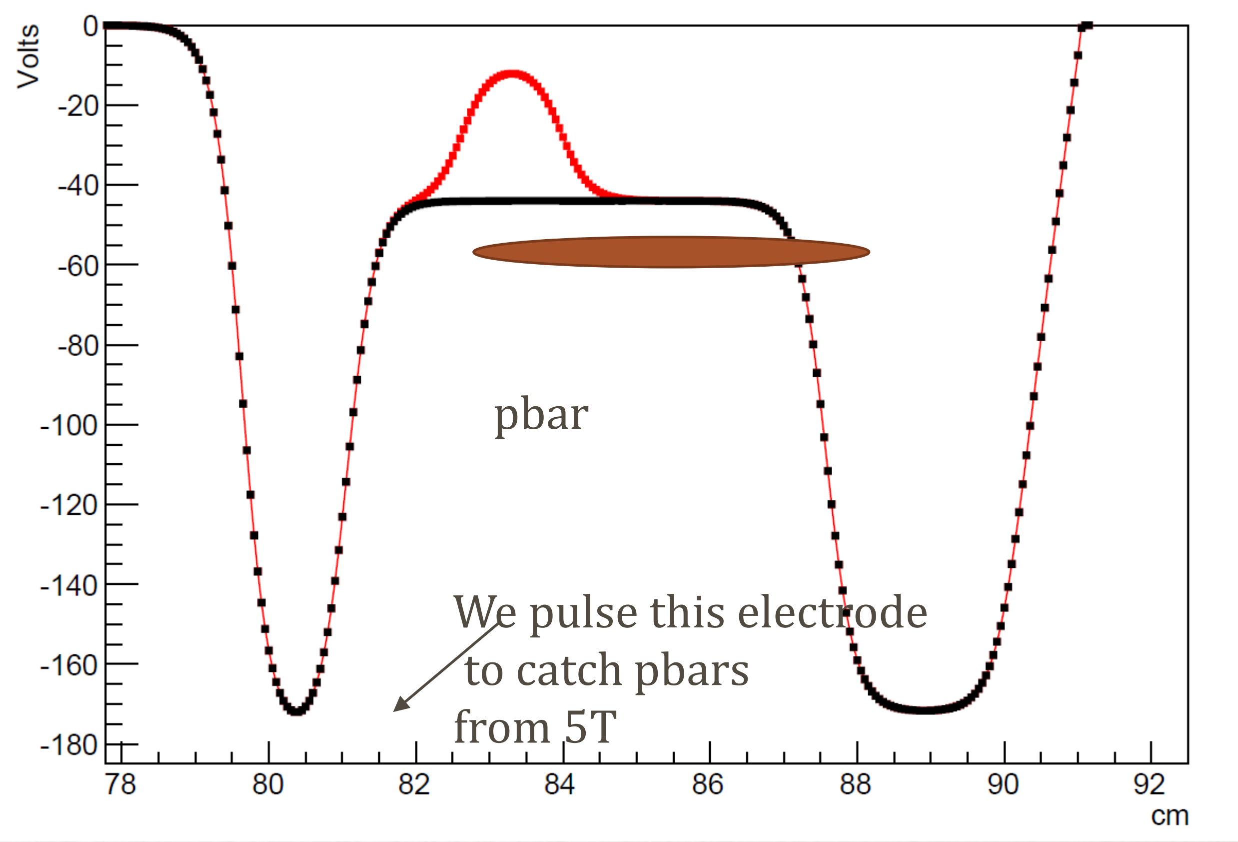
Antiproton cooling in the Hbar formation trap

- Present setup: electron cooling
- Pbar energy after balistic transfer: some eV
- Need to load electrons in the Hbar trap
- Can we create a inner potential well preloaded with e-???
- As in the 5T region….

We observed antiproton radial transport and instabilities enhanced by radial electric field also wihout electrons

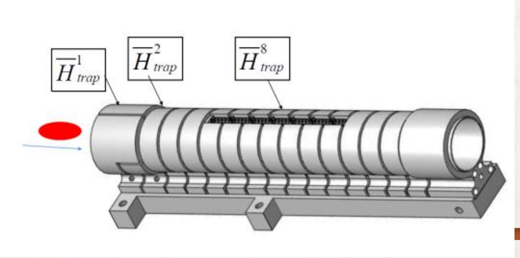
Losses without (and with) e-

1T Hbar formation trap

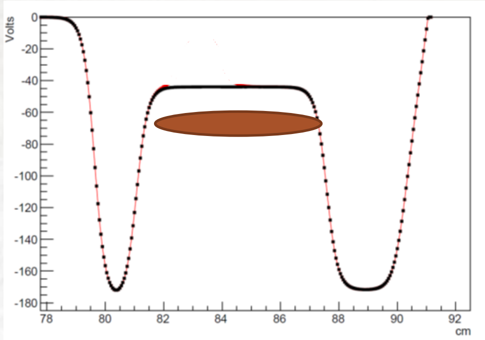


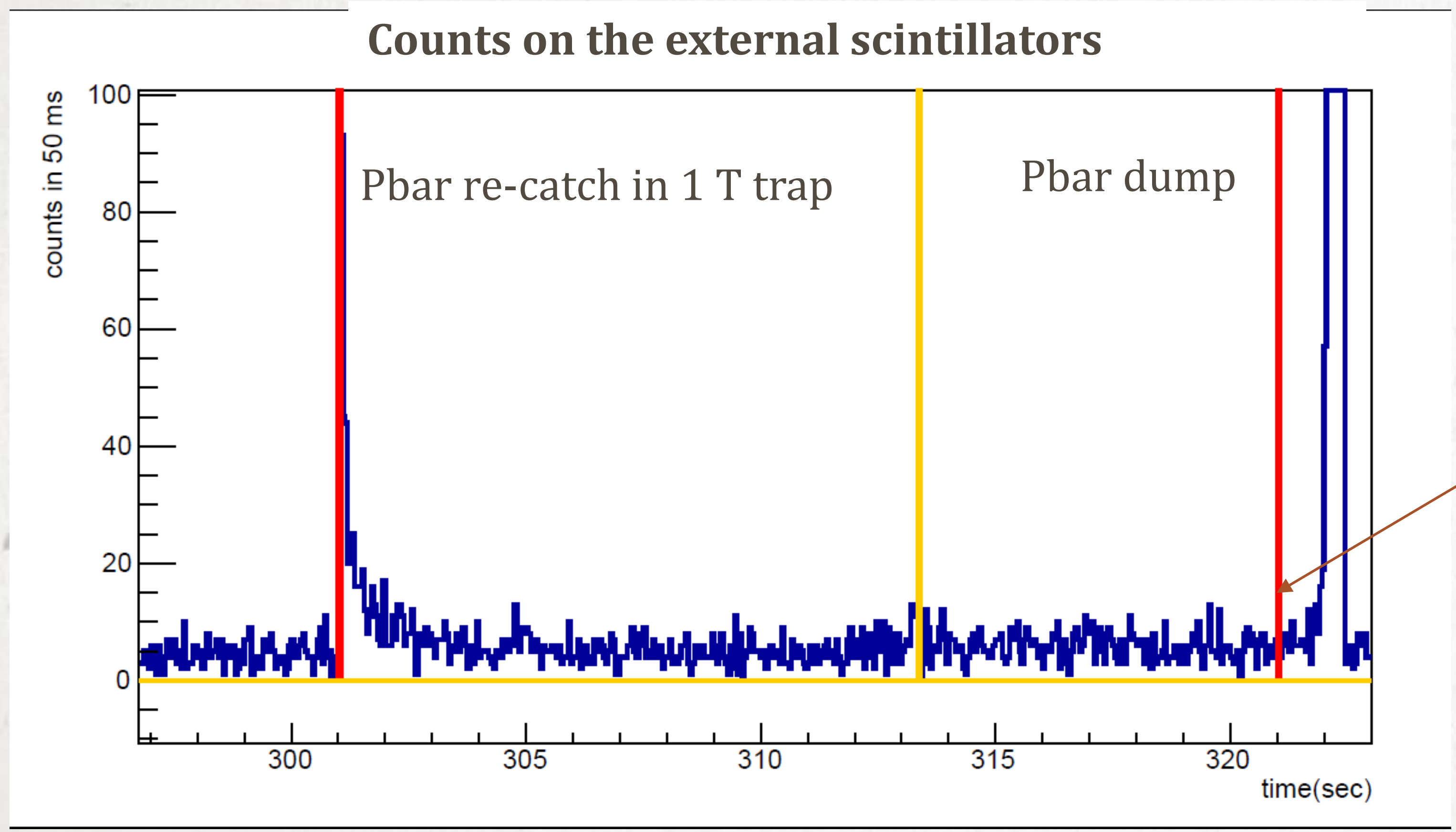
pbar

We pulse this electrode to catch pbars from 5T



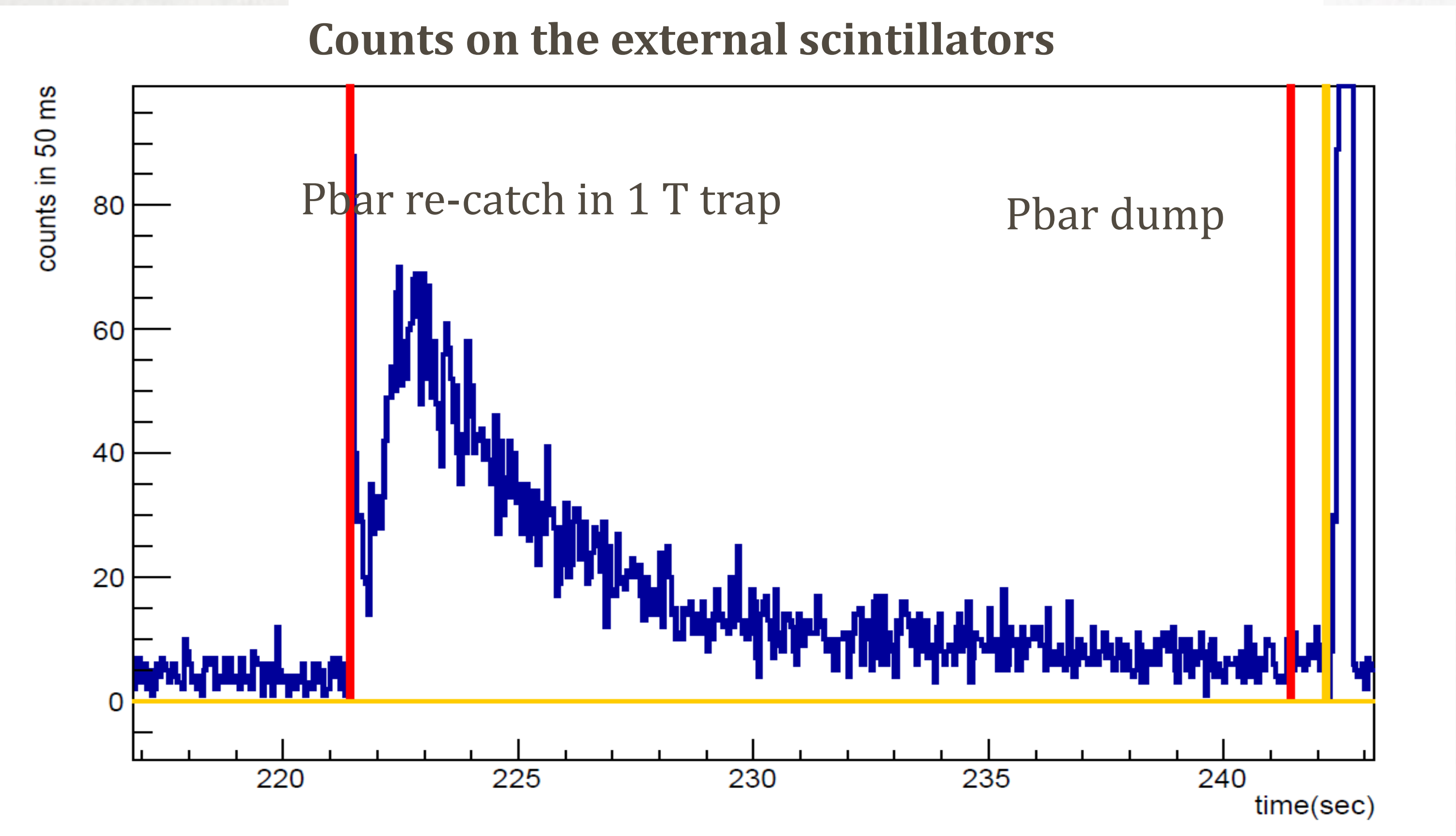
OBSERVED RADIAL TRANSPORT ENHANCED BY RADIAL ELECTRIC FIELD

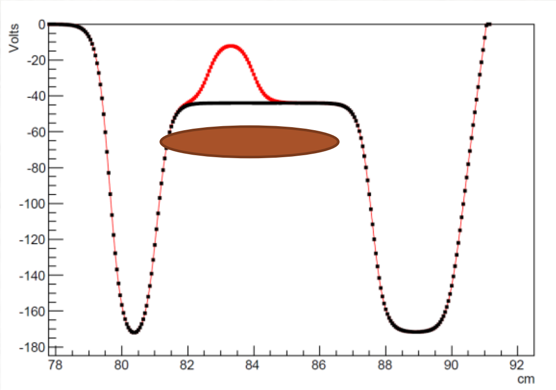



Counts on the external scintillators

- **No inner potential well**
- (no electrons)
- 20 sec storage time
- Slow dump
- counts on external scintillators
- 2 10^5 antiprotons

OBSERVED RADIAL TRANSPORT ENHANCED BY RADIAL ELECTRIC FIELD

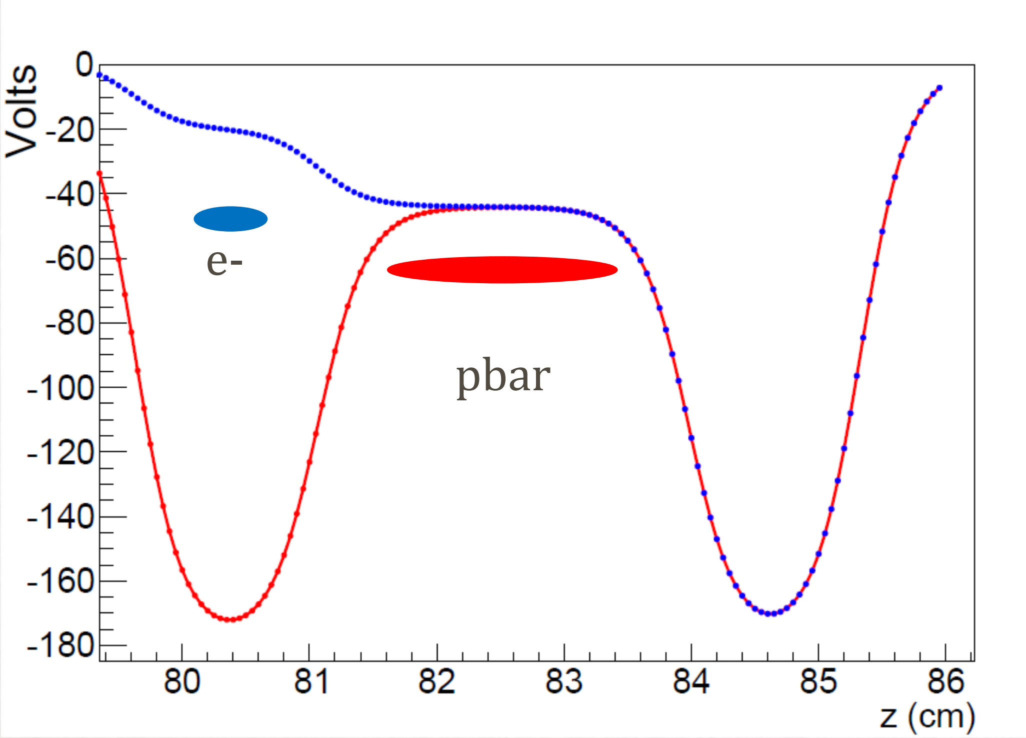

Counts on the external scintillators



With inner potential well

- No electrons
- 20 sec storage time
- Slow dump
- counts on external scintillators
- $3\ 10^4$ antiprotons in the dump ! 1/10 !!
- Losses depend on the height of the inner potential well

Antiproton cooling in 1T: re-Catch pbar and e- in the same potential well



- **Catch pbar with balistic method**
- Prepare and park with RW e- plasma in the Big trap@1T
- Catch e- with pbar inside
- Balistic transfer of e-
- Open trap with fast pulses (few tens ns)
- Typically some 10^7 electrons

- Cool pbar for few tens sec

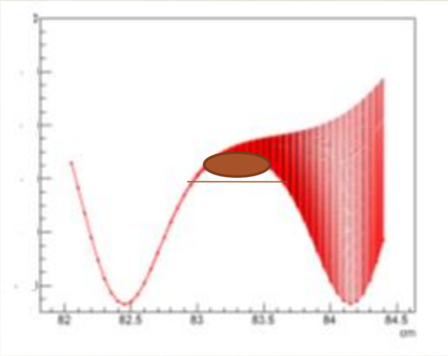
- Reduce the number of e-

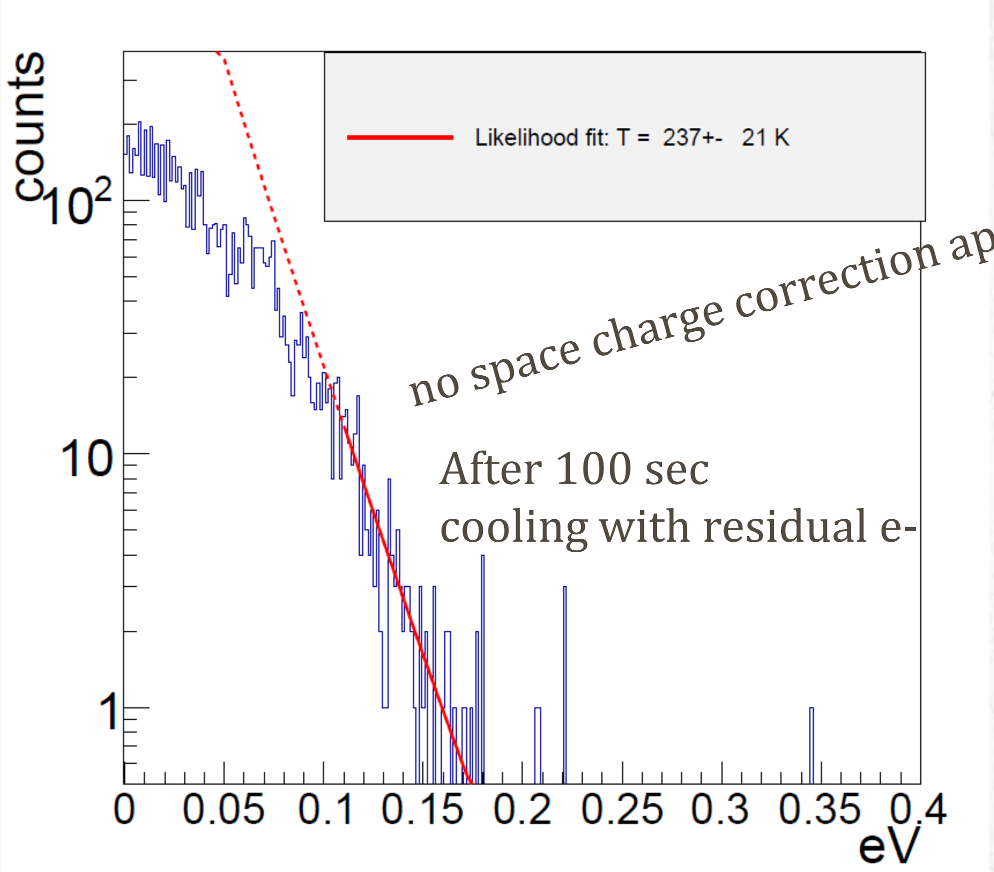
→ Limit the radial transport

→ Measure the pbar temperature

2 10^5 pbar /AD shot cooled in the Hbar formation trap

Pbar temperature @1 T with few electrons





no space charge correction applied

After 100 sec
cooling with residual e-

Residual number of electrons: below 10^6, some 10^5
Inferred from the cooling effect on pbars

Maxwell distribution of axial velocities
Number of particles escaping the potential W

$$\frac{dN}{dW} = \frac{A}{\sqrt{W\ KT}} \exp^{-\frac{W}{KT}} + B$$

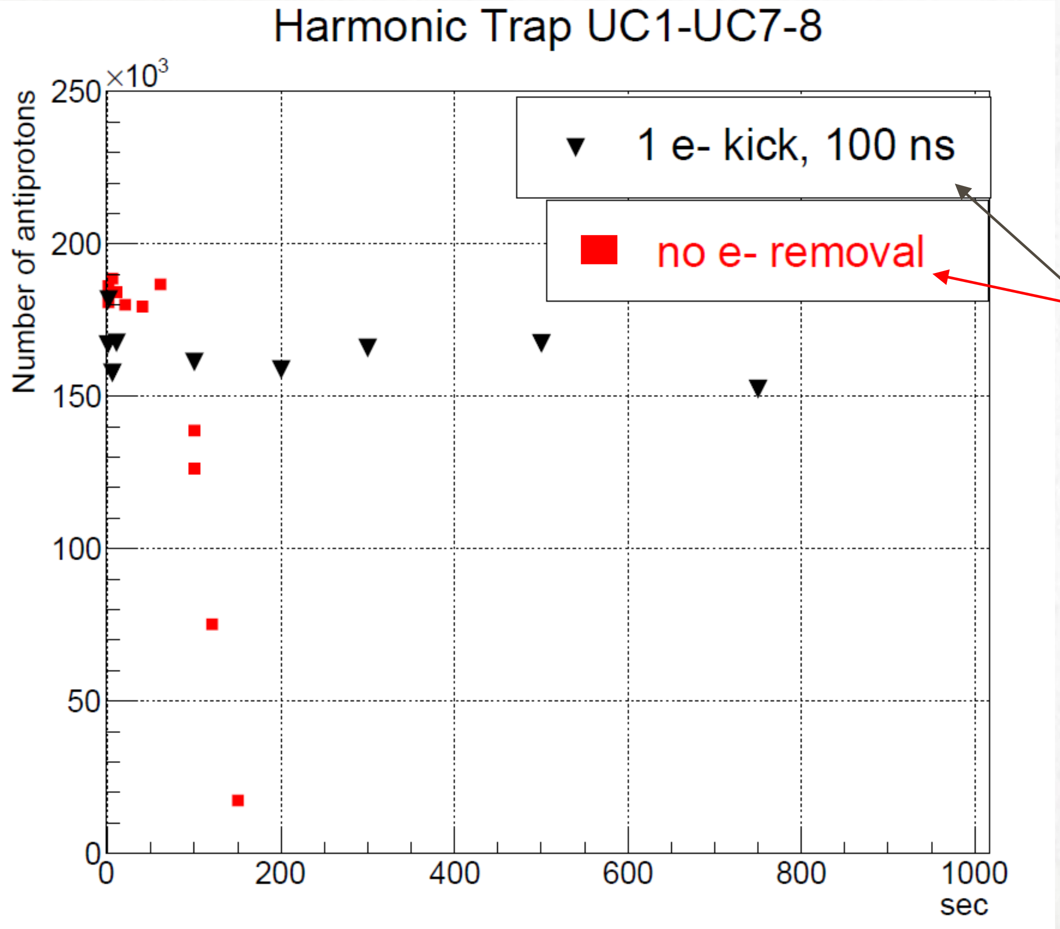
Slow release of the potential barrier W and count N(W)

Known complications:
Height of the potential well depends on radial position
First partcles exit from near the axis
Space charge influences the potential well
Use only the first few particles extracted

Pbar temperature influences the Hbar detection efficiency: see later……………………
Measured values do not limit Hbar detection

Procedure similar to G. Gabrielse et al., PRL 106 073002 (2011)

Mixed plasma dynamics: antiproton radial transport induced by electrons plasma expansion



Long pbar storage time achieved with few e-

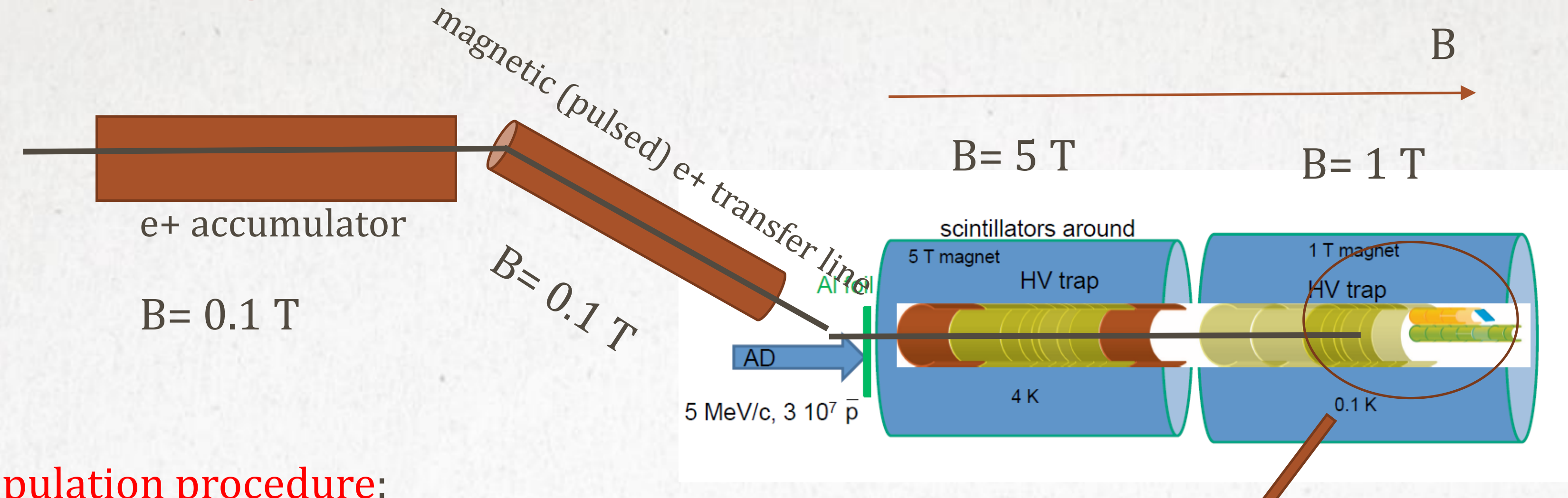
Mixed plasma with the same pbar and
1-2 10^7 electrons or
less than 10^6 electrons

Pbar expansion rate driven by that of the electrons
(data in the 1T antiH formation trap)

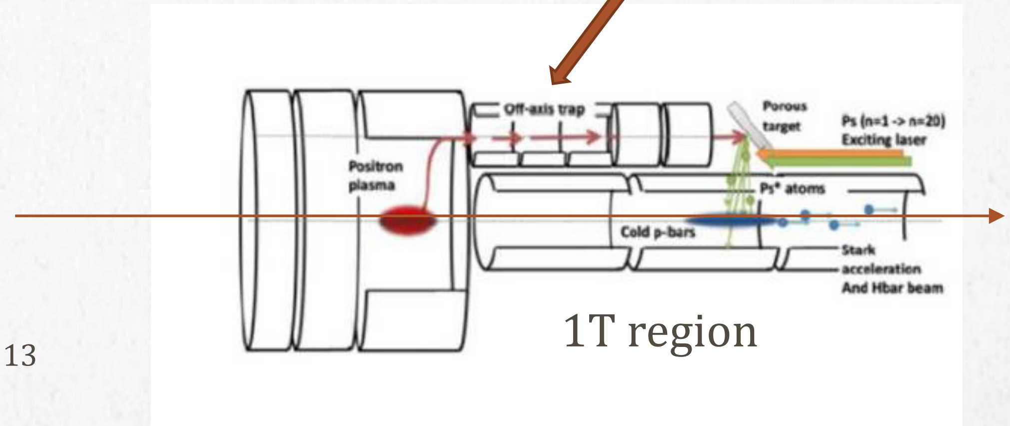
Dynamics similar to that of the compression

Hbar formation procedure: use less than 10^6 e-

e+ transfer: original proposal



e+ manipulation procedure:



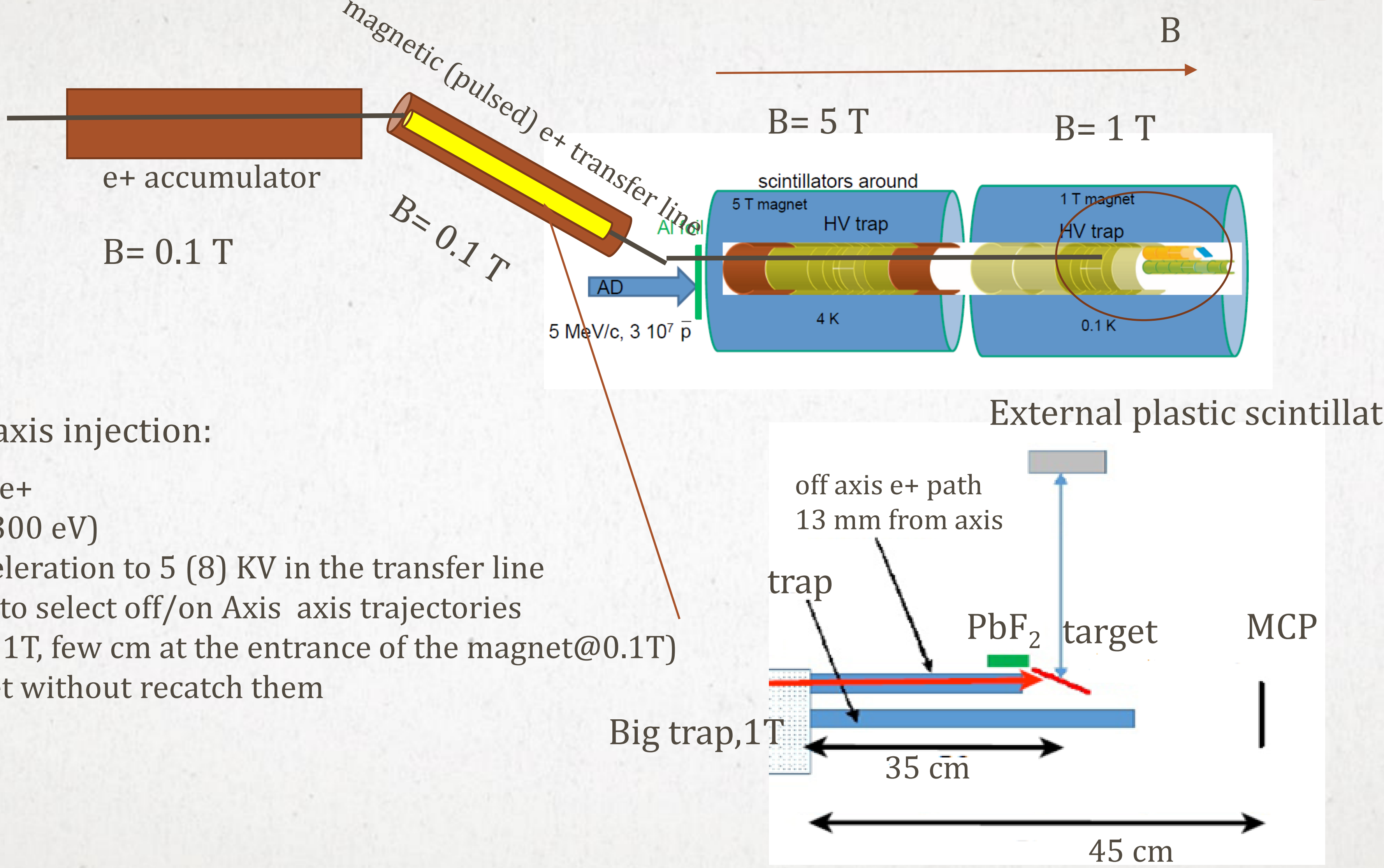
1) Accumulate e+
2) Transfer e+ (300 eV)
3) Catch in 5 T, do RW
4) Transfer toward 1T
5) Make e+ diocotron excitation

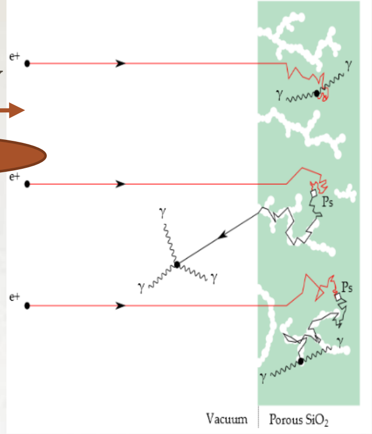
see AegiS Coll Hyperfine Intercations 2015, Volume 233, Issue 1–3, pp 13

1) Recatch e+ in the off axis trap
2) Accelerate in the off axis (few KV) toward the Ps formation target 1.5 cm off axis

e+ direct injection: present setup

Implemented during 2016





Direct off axis injection:

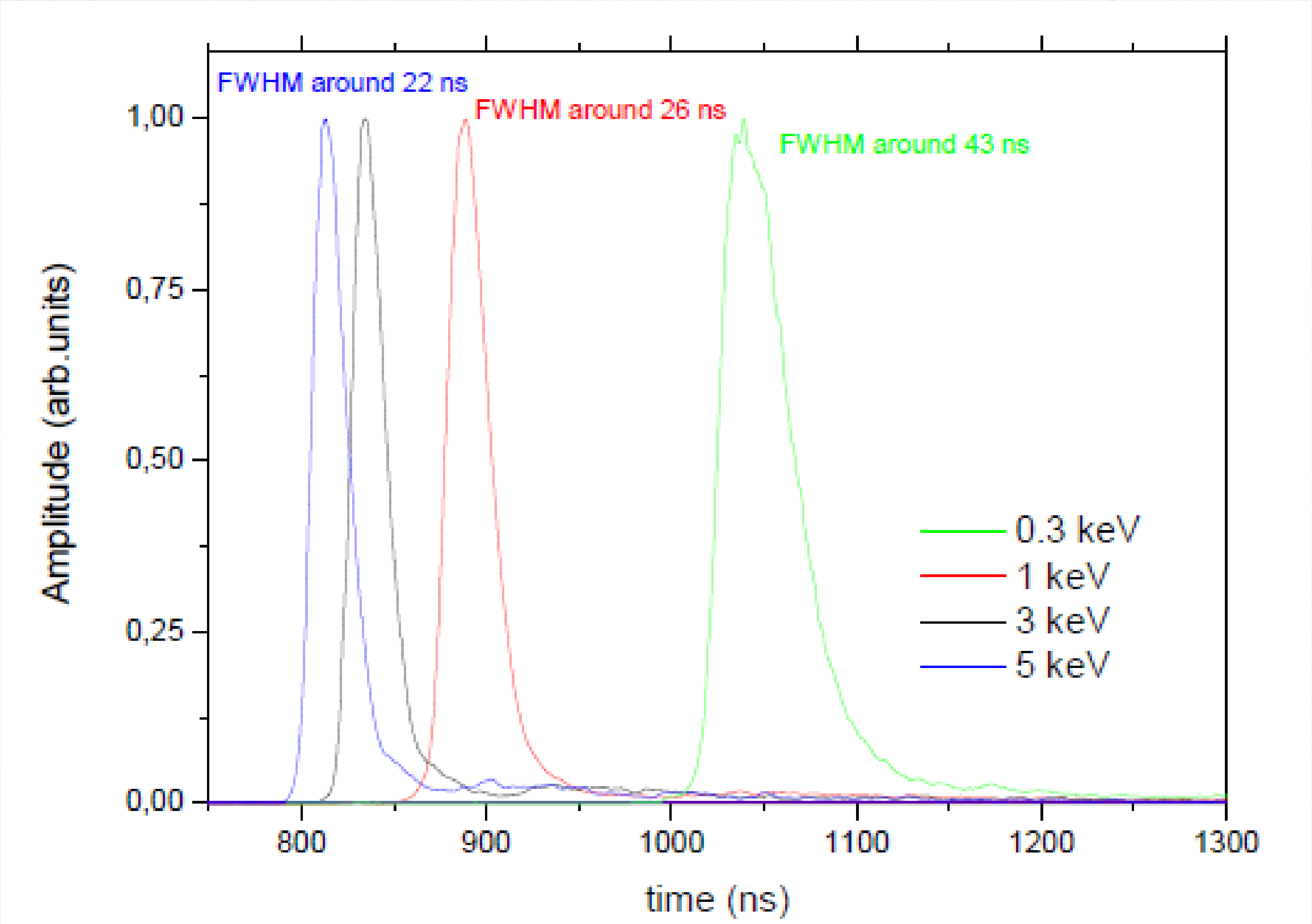
1) Accumulate e+
2) Extract e+ (300 eV)
3) In flight acceleration to 5 (8) KV in the transfer line
4) Pulsed coils to select off/on Axis axis trajectories

(1.3 cm of axis@1T, few cm at the entrance of the magnet@0.1T)

1) Hit the target without recatch them

e+ time compression and impact time vs Kicker HV

Normalized Volts



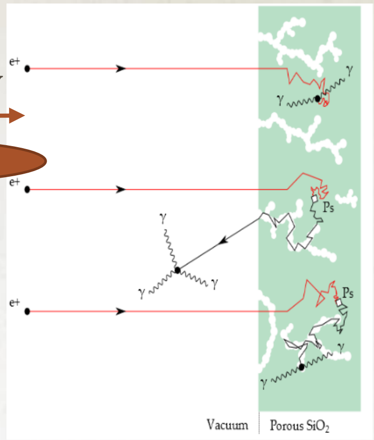
Scintillator signal vs time
Analog readout of the PMT signal

e+ hit the target with 20-30 ns

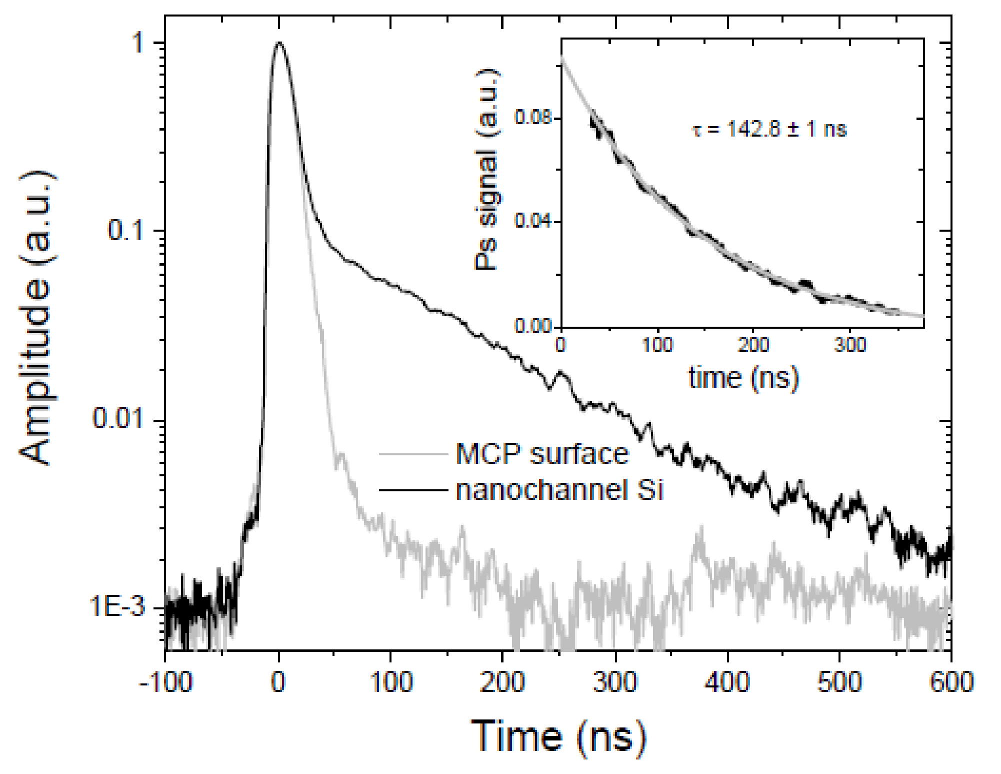
Positronium detection in the AEgIS test setup

E= some keV

e+



AEgIS:positron test setup



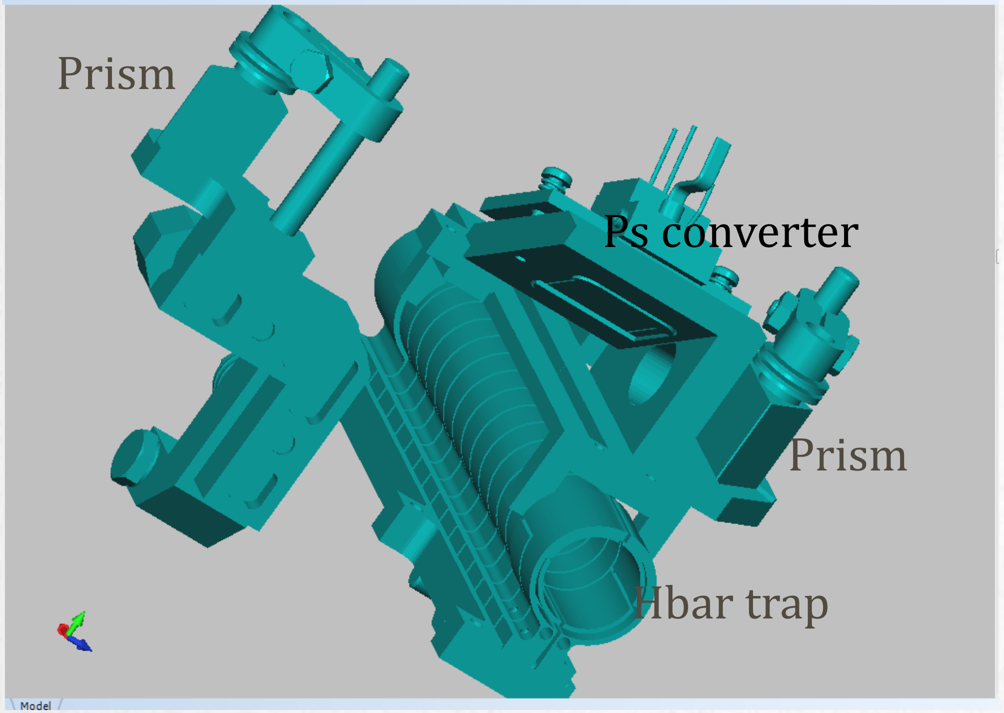
Fast detector; PbF_2 +PMT
Analog output of the PMT digitized
(Single Shot Positron Lifetime Spectroscopy: SSPALS)
Average of 10 meas.

Prompt peak + tail due to Ps formation and decay with 142 ns

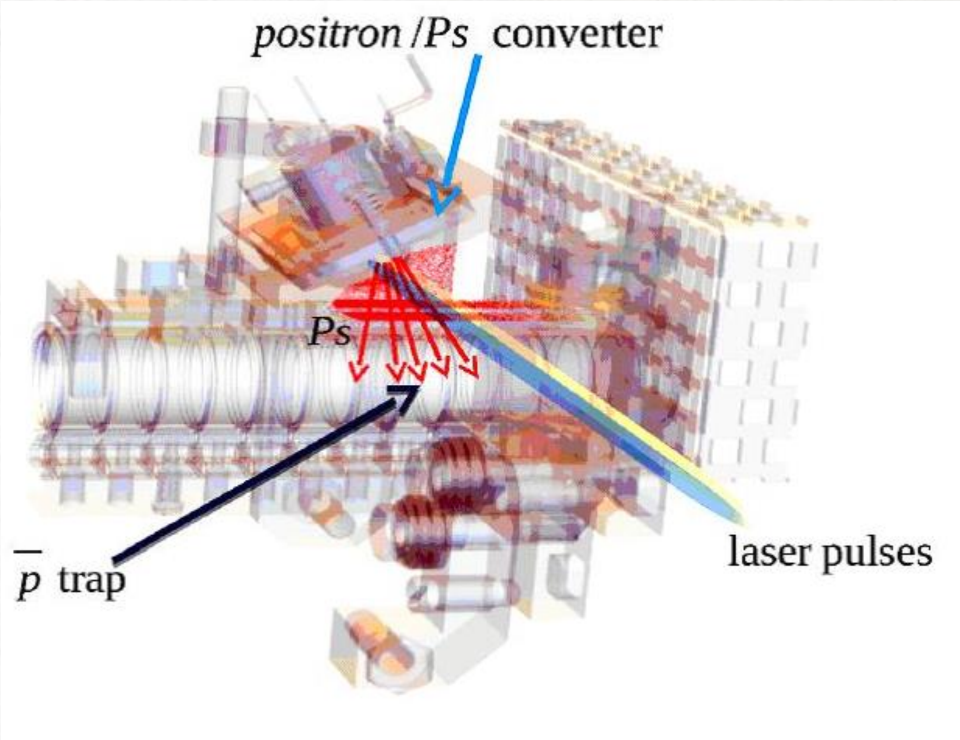
Ps yield
Tail/Peak+Tail =35% with the implantation energy 5 KeV

Expected Ps yield in 1T is 2/3*35%=23%

Positronium detection in the 1 T region

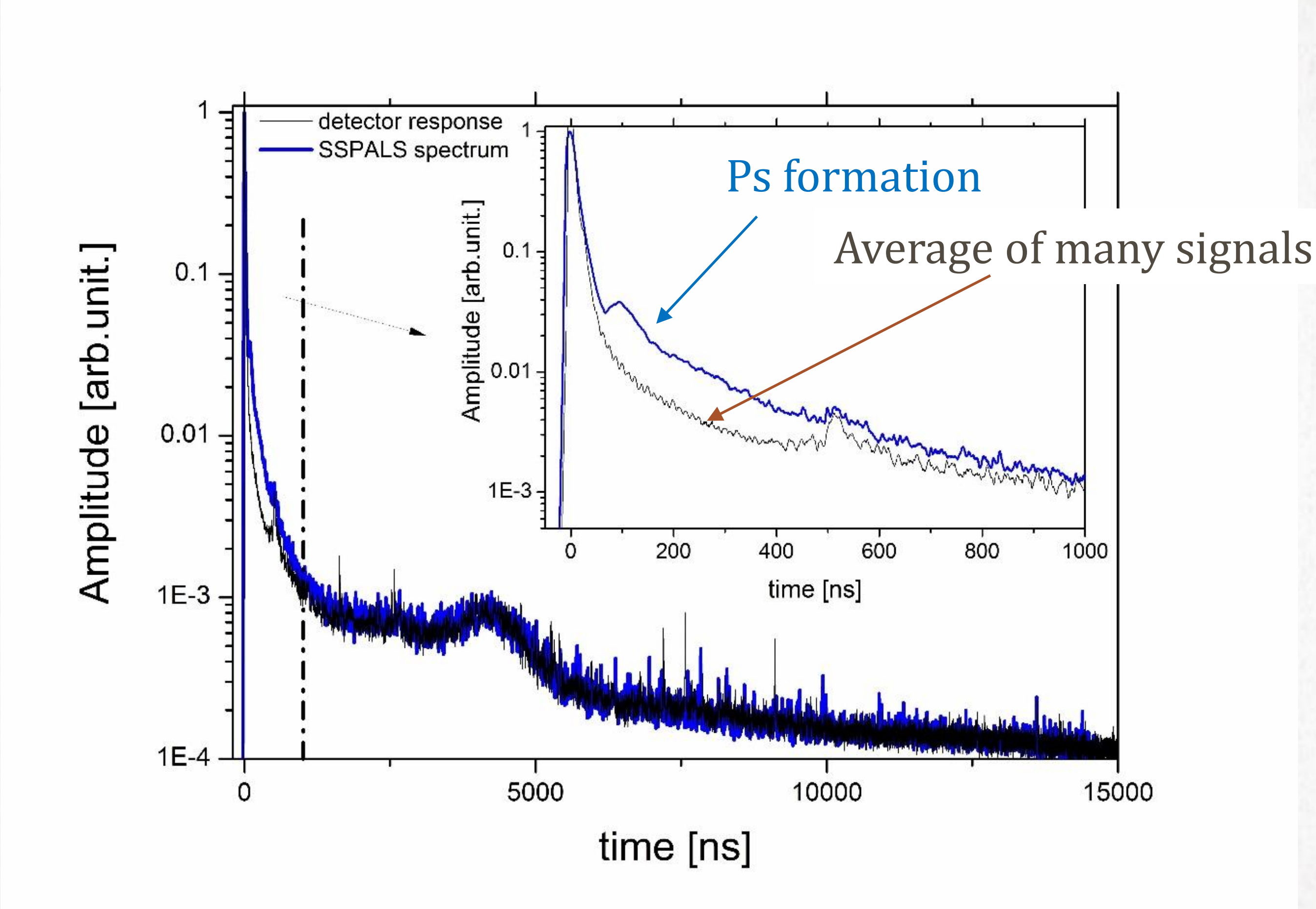


Several obstacles along the Ps path
Structures in the time signal



Monte Carlo code including the true CAD drawing
Annihilation due to lefetime+ Ps hitting obstacles
(trap, support structures)

Positronium formation in the 1T region



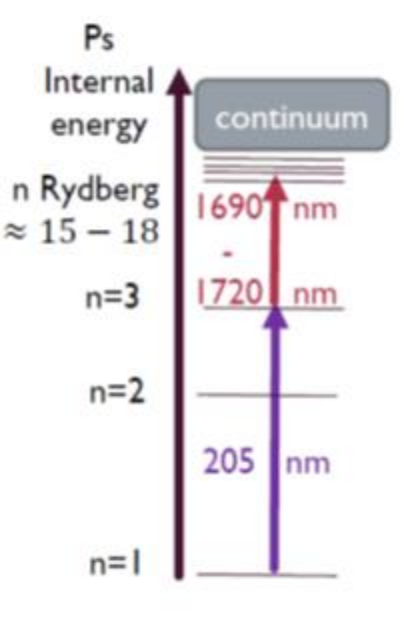
Ps formation

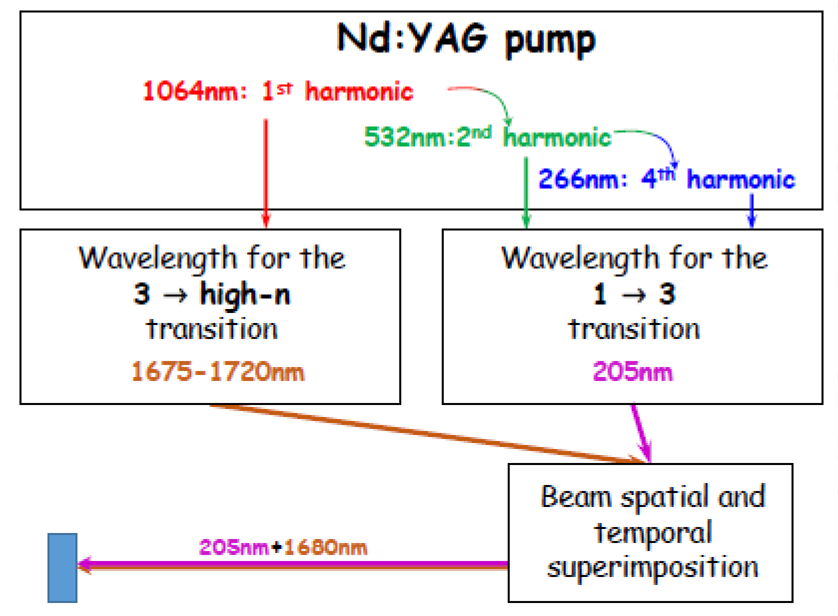
Average of many signals due to cosmics

Target in 1 T region
T= 10 K

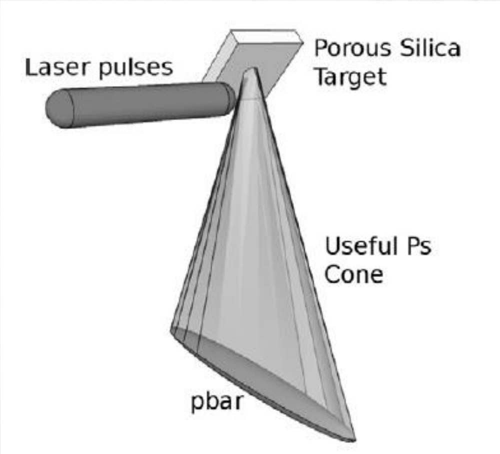
Detection: EJ 200 plastic scintillator +PMT
analog signal on FAST (2.5 Gs/s)
high resolution digitizer

2 steps Positronium laser excitation



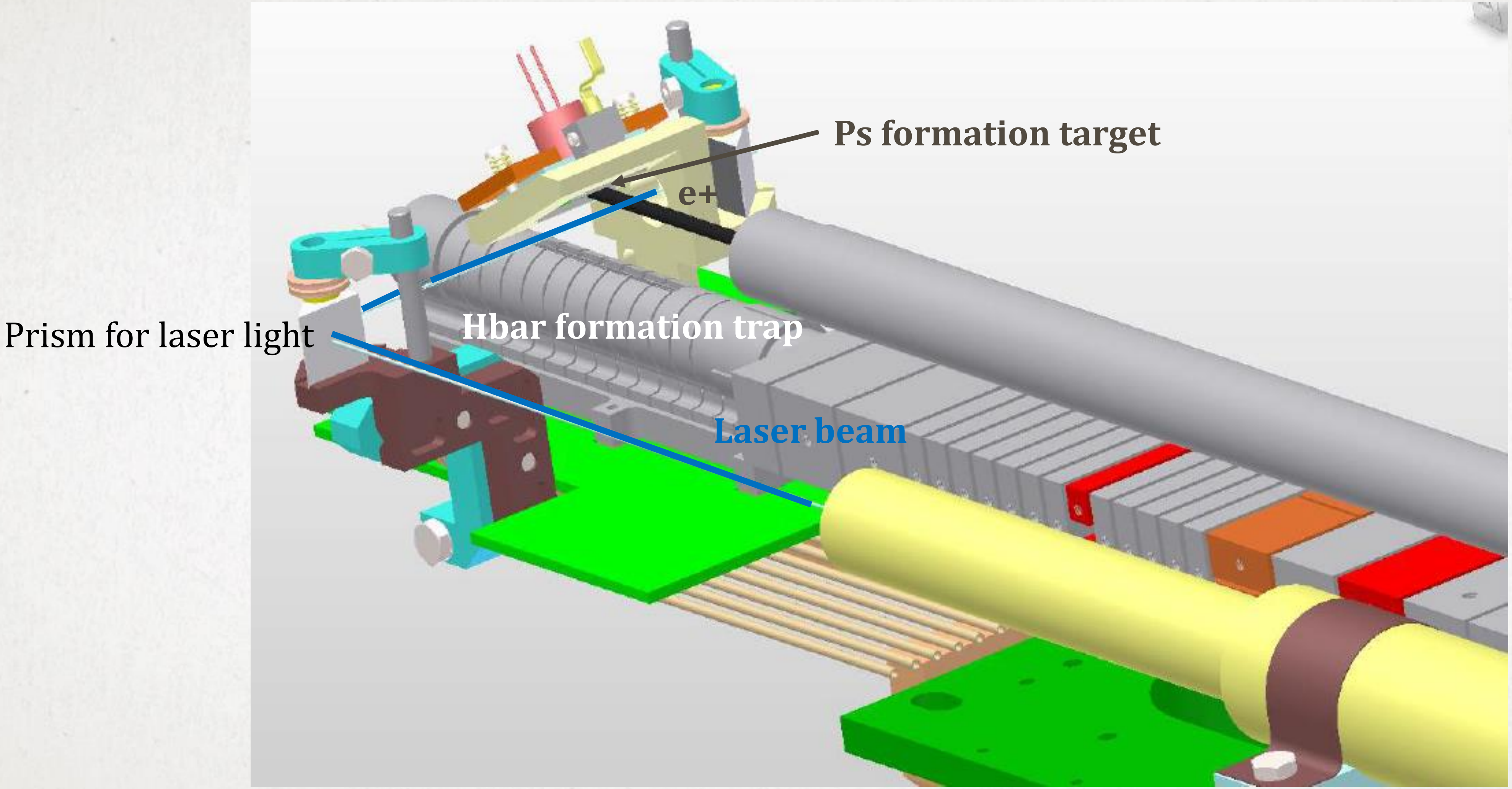


UV 205.047 nm	IR 1680-1715 nm
1.5 ns	5 ns (2 ns delay with respect to UV)
3mm FWHM	3.5 mm FWHM
90 µJ	1 mJ



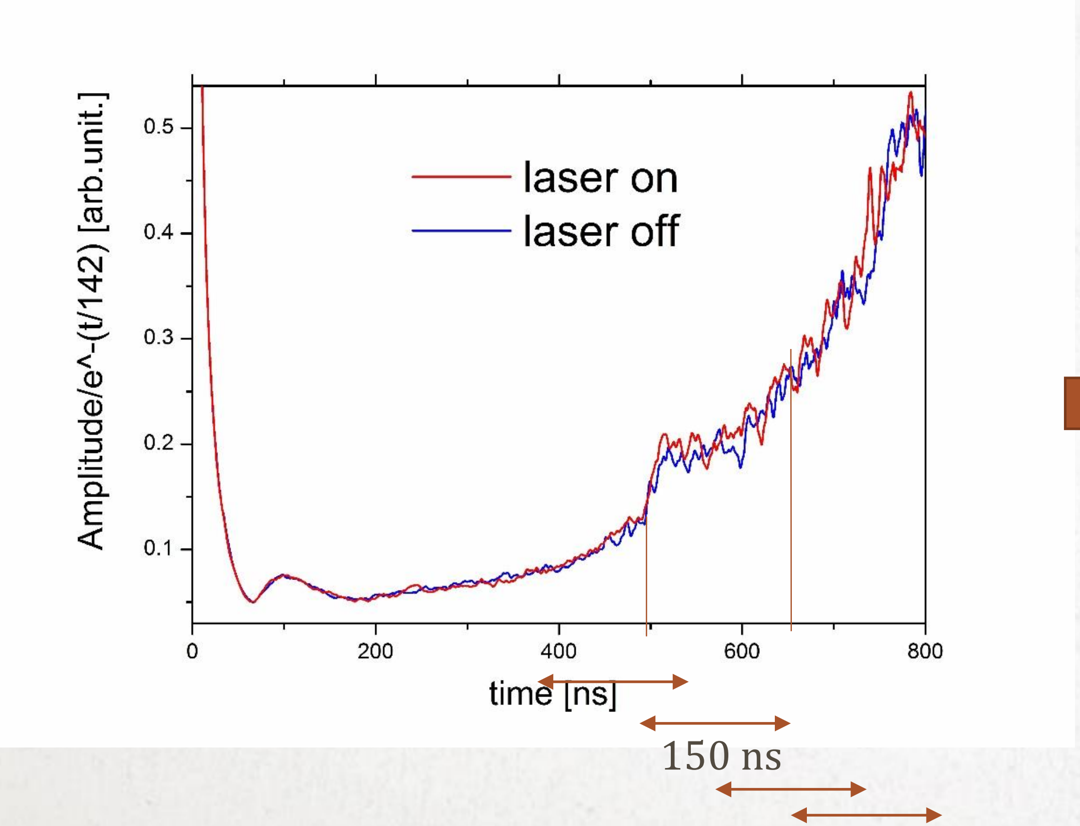
Already demontrated by us in the e+ test setup

The laser in the 1T interaction region



Rydberg Ps formation in 1T region

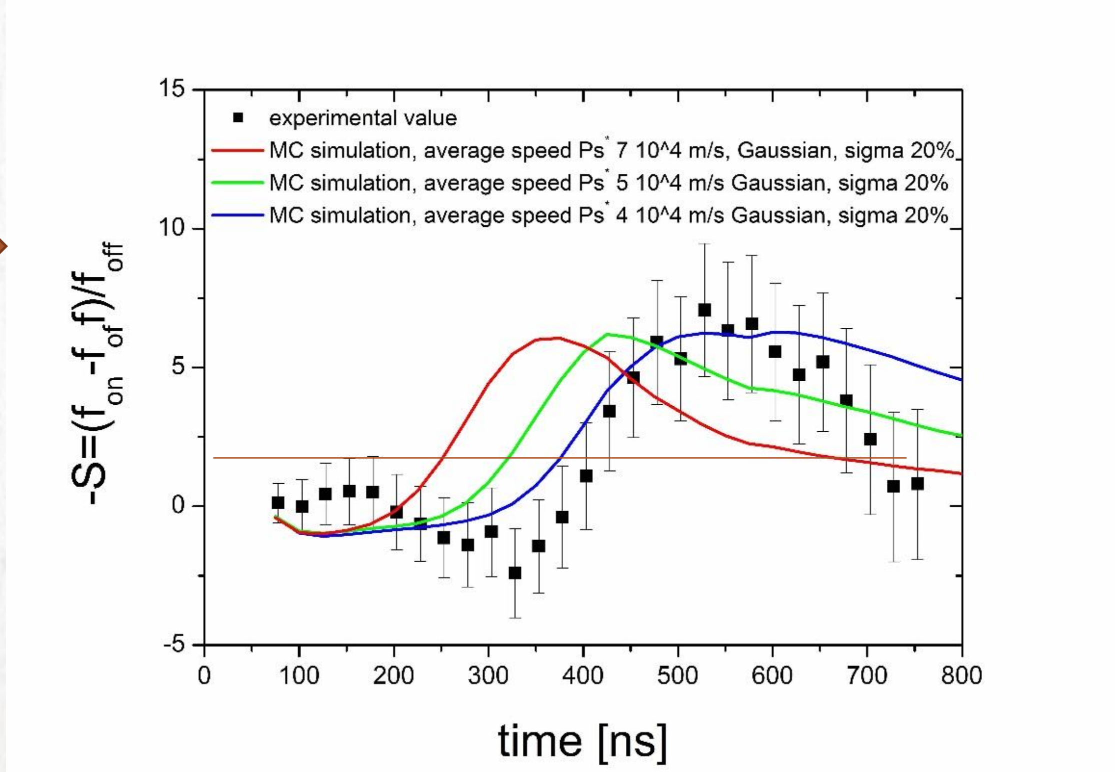
- Alternate laser on and laser off
- Look at differences in the tail of the scintillator signal
- Compare with MC
- Rydberg Ps has a longer lifetime than ground state Ps
- If excited, Ps atoms can reach obstacles at large distance
- We should see more annihilation at later time



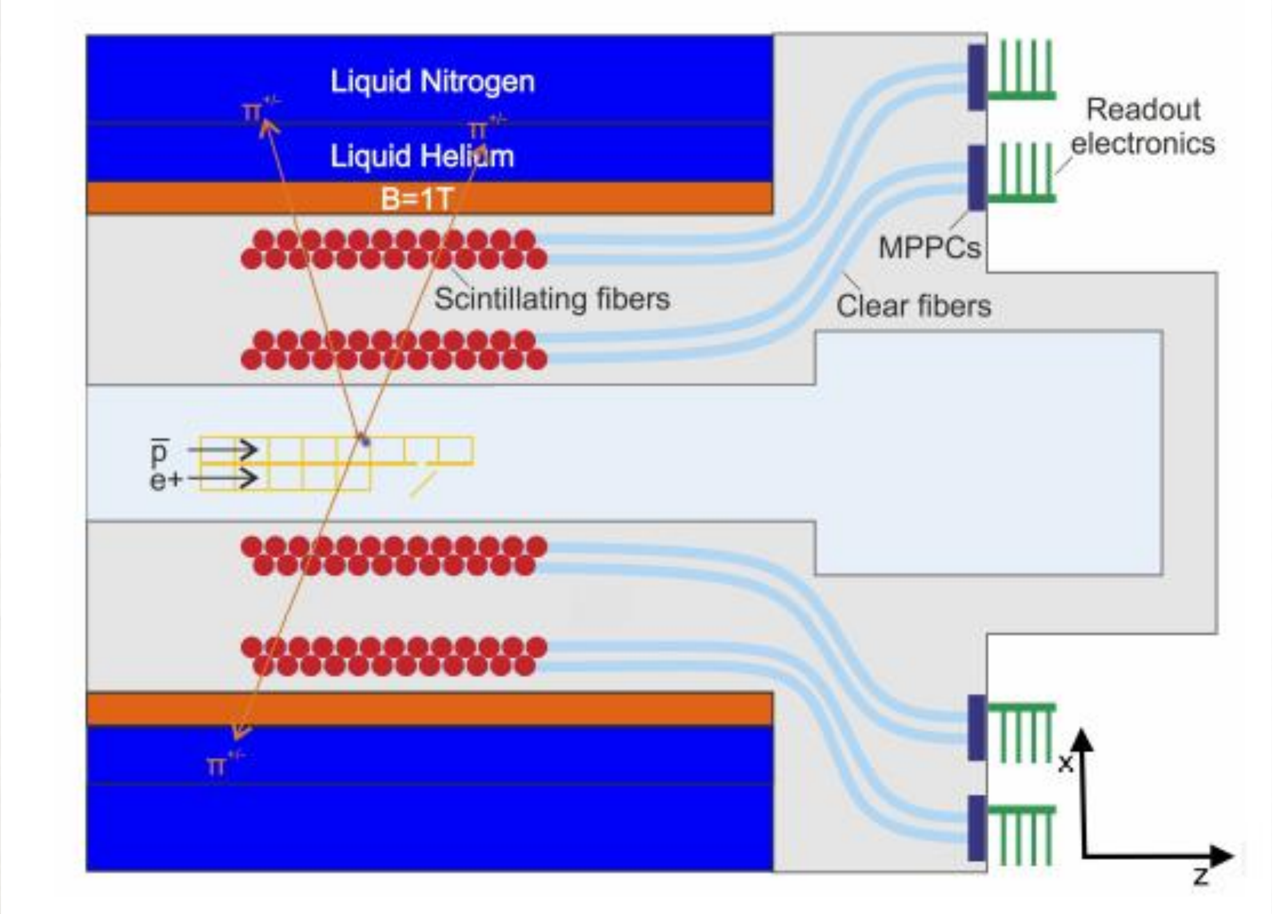
150 ns

nPs=17 (if B=0)

Diff. of the signal area (f) within 150 ns moving window (25 ns step)



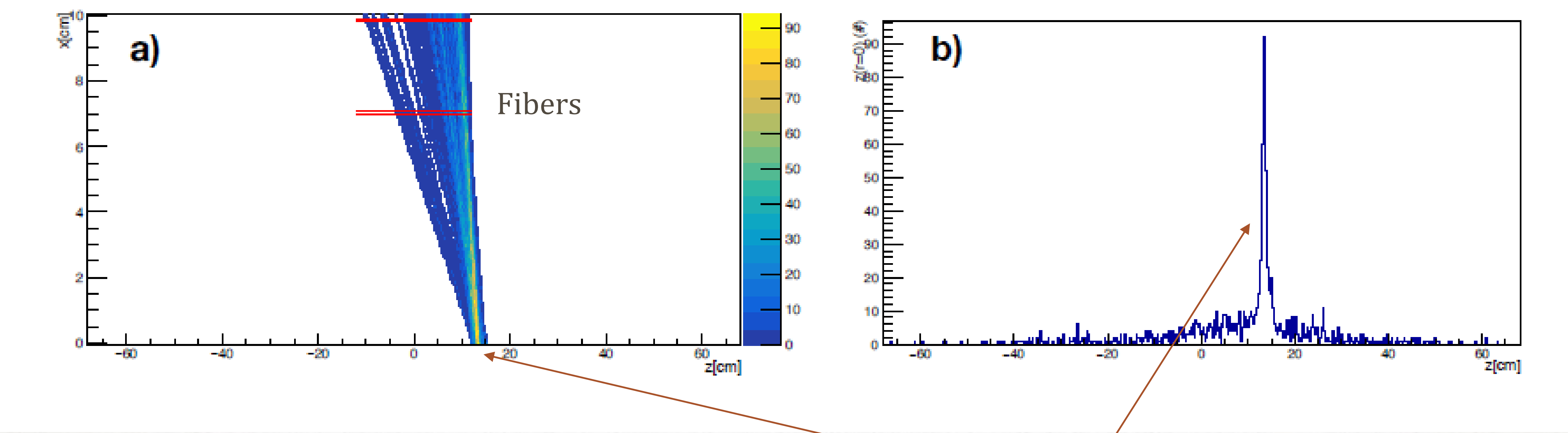
Antihydrogen detector: Fast Antihydrogen Cryogenic Tracking - FACT

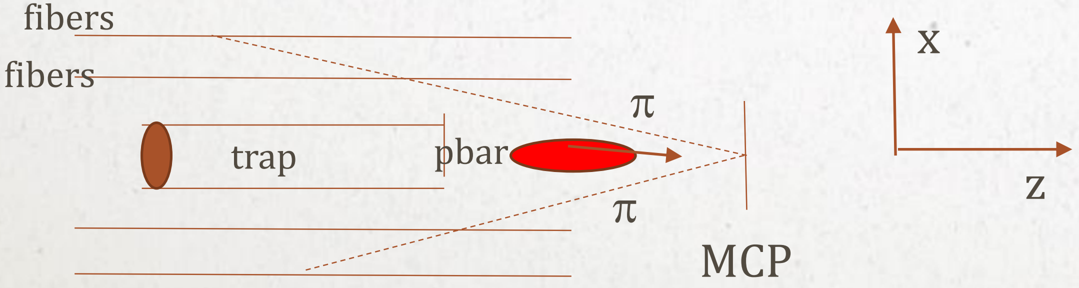


- It surrounds the Hbar production trap
- About 800 scintillating fibers@4-10 K
- 2 (double) layers
- z and r resolution (no Phi)
- Readout: SiPm (MPPC from Hamamatsu)@300K
- Digital readout: counts above threshold
- Time over Threshold
- 200 MHz sampling (5 ns time step)
- Threshold and bias individually controlled
- Typical signals: 7mV @1 phe
  pions : 15-20 phe

Track and vertex reconstruction

PBAR DUMP ON MCP: TRACKS WITH FACT



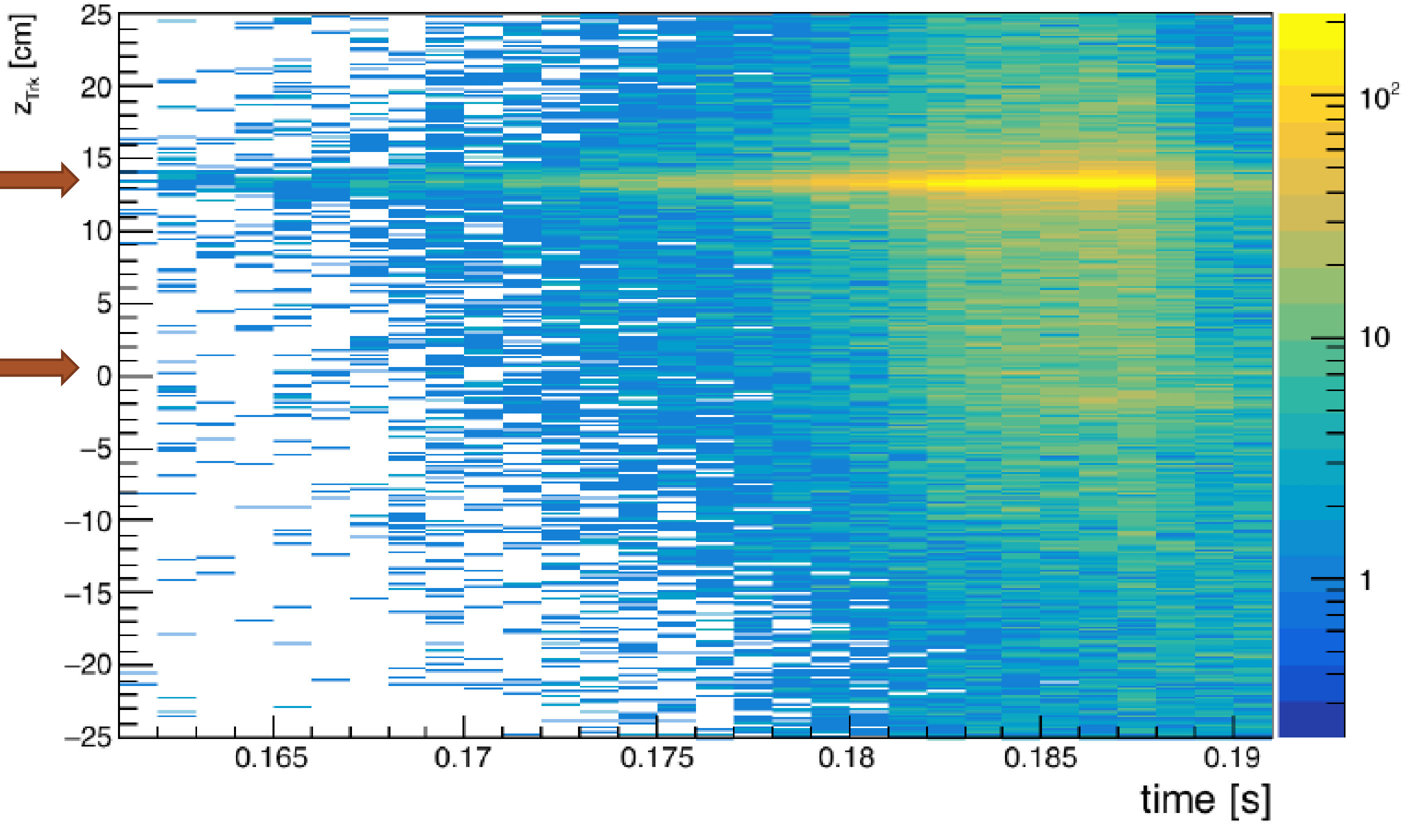


- MCP position reconstruction accuracy: 4 mm
- Resolution: close to 1mm
- Efficiency: need to be improoved

Time resolved antiproton tracking with FACT

MCP position

Trap



z- time distribution of reconstructed tracks
Slow dump of pbars on MCP
Pions with z= trap position
(radial losses during the dump
at late time in the ramp)

Antihydrogen Formation&Detection

Prepare pbar in the 1T trap as described

Stack 2 shots in the 5 T Trap, compress &transfer 3-5-4 10^5 pbars (4 times more pbar then what expected in the proposal)

Trigger e+ accumulator& laser & make Rydberg Ps

Rydberg Ps fly through pbar and make Hbar

Hbar move toward the trap electrodes
Collected many data since September 2017

Detection: search for Hbar annihilation within few microsec after the prompt peak due to e+
proper set of threshold to avoid afterpulses
Blind the detector for at least 500 ns
Compare laser off and laser on

DATA ANALYSIS IN PROGRESS

ADDITIONAL WORK: TOWARD COLDER ANTIPROTONS

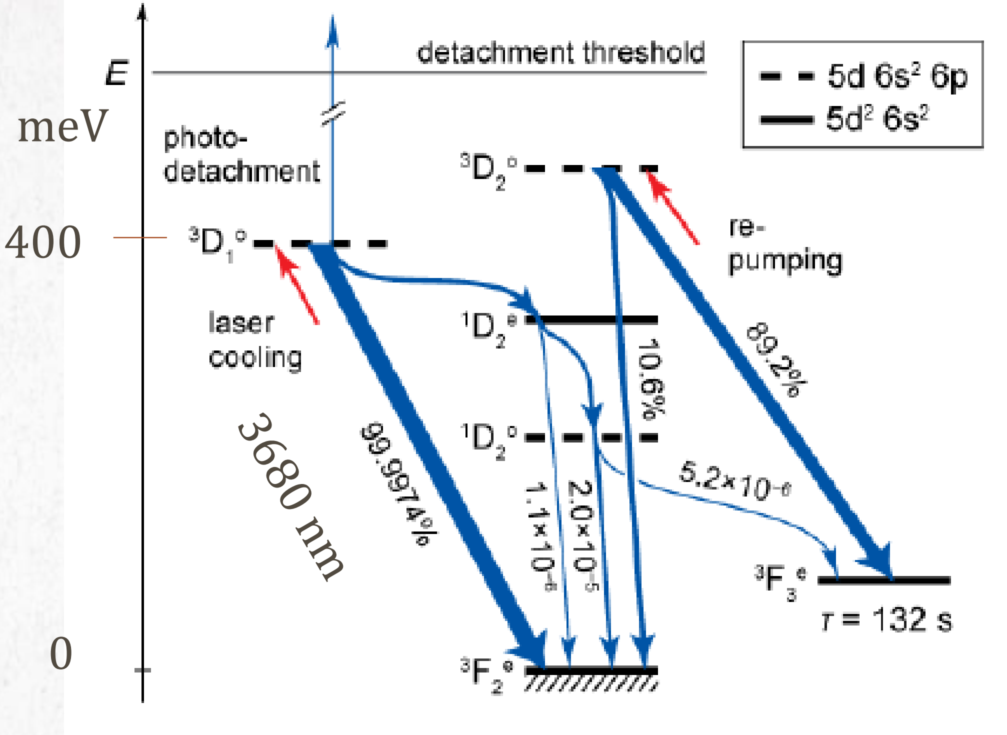
Experimental setup separated from the AEGIS apparatus

1) Laser cooling of anions: Lanthanum La$^-$ (Heidelberg)
Laser cooling to be tested soon in a Paul trap

2) C$_2^-$ @CERN
C$_2^-$ source commissioned, trapping ongoing
tests intercation with laser very soon

Sympathetic cooling of pbars modeled
J. Fesel et al., Phys. Rev. A 96 031401 (2017)

La- level scheme



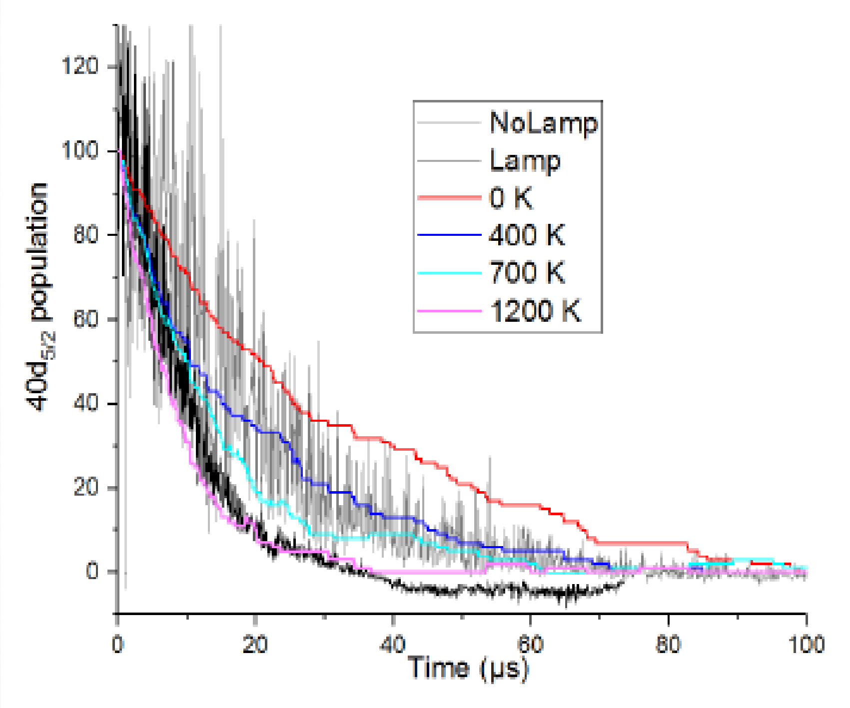
Cooling from 100K to TD=1.6 μK in 3.7sec
About 10^5 photons absorbed

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

ADDITIONAL WORK: RYDBERG ATOMS DE-EXCITATION

TeraHz radiation (mercury lamp) to accelerate the decay of Hbar Rydberg atoms
Create black body radiation at temperature T and enhance the decay (stimulated emission)
10 mW/cm2   0.1-5 THz
Tested with Cs atom

Cs atoms excited to n=40



CONCLUSIONS

- Commissioning of all the subsystems
- Half of the 2017 run time devoted to antiH production trials
- Data analysis in progress
- Improovements in the diagnostic under preparation
- Hbar production work will continue during the 2018 run
- We ask for the usual pro-rata allocation of the beam time

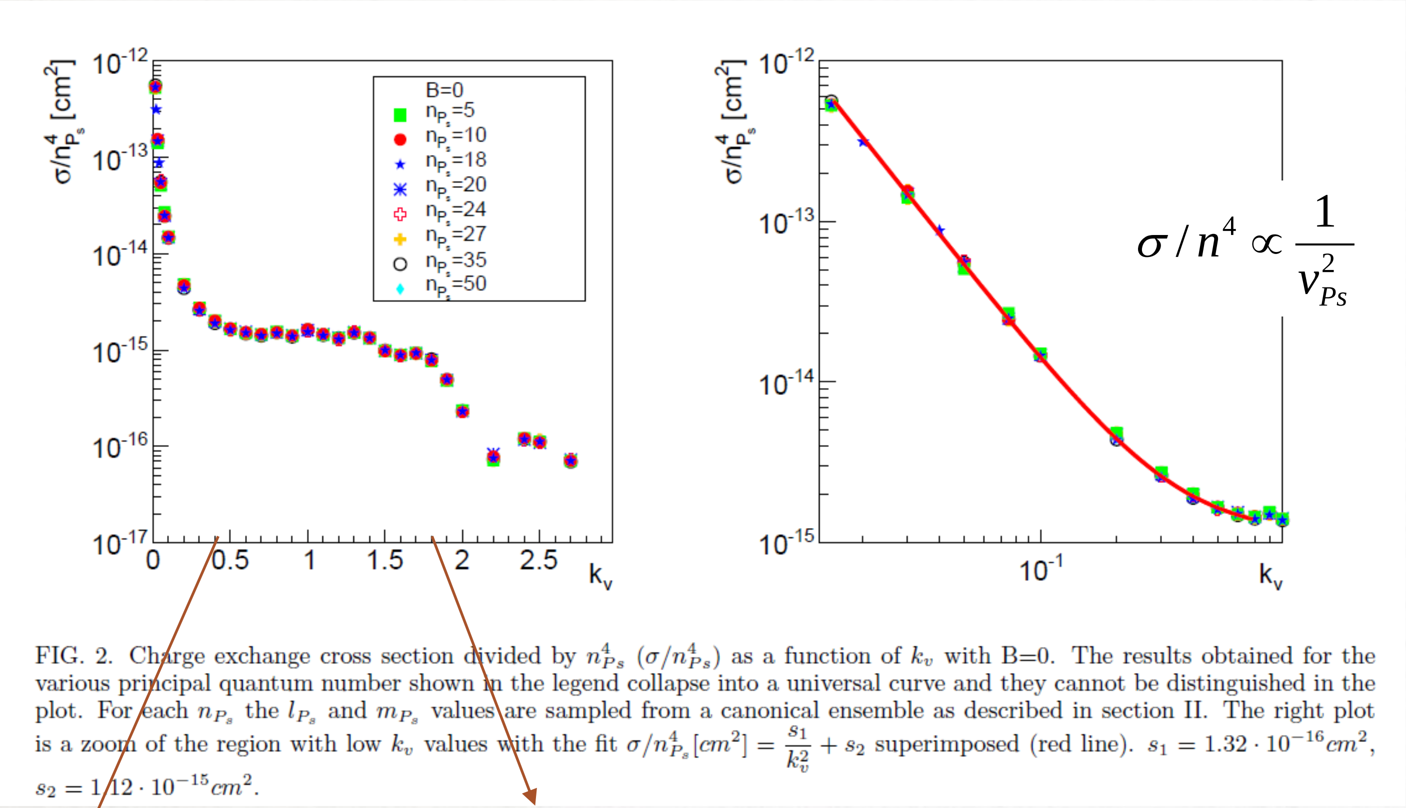
Parallel work about

- antiproton cooling to subK temperature
- Rydberg antiH de-excitation

- Move the apparatus in the new zone during LS2
- ECR request prepared, under evaluation

Thanks to the AD team, the cryolab and all the support from CERN!!

Charge Exchange cross section



$$\sigma / n^4 \propto \frac{1}{v_{Ps}^2}$$

FIG. 2. Charge exchange cross section divided by n_{Ps}^4 (σ/n_{Ps}^4) as a function of k_v with B=0. The results obtained for the various principal quantum number shown in the legend collapse into a universal curve and they cannot be distinguished in the plot. For each n_{P_s} the l_{P_s} and m_{P_s} values are sampled from a canonical ensemble as described in section II. The right plot is a zoom of the region with low k_v values with the fit $\sigma/n_{P_s}^4[cm^2] = \frac{s_1}{k_v^2} + s_2$ superimposed (red line). $s_1 = 1.32 \cdot 10^{-16} cm^2$, $s_2 = 1.12 \cdot 10^{-15} cm^2$.

$v_{Ps} = 3\ 10^4 m/s$

if nPs=17

$v_{Ps} = 1.2\ 10^5 m/s$

if nPs=17

D. Krasnicky, C. Canali,R. Caravita, G. Testera
Phys. Rev. A **94**, 022714 (2016)

Classical Calculation $\sigma \propto n^4$

$$\left(v_{cm}^{Ps}\right)_{m/s} = \frac{k_v}{2\ n_{Ps}} 2.19\ 10^6 m/s$$

A.S. Kadyrov et al.
Nature Comm. 8, 1544 (2017)

Quantum calculation $\sigma \propto n^2$

Classical regime restored if $\lambda_{dB} < 2a_0 n_{Ps}^2$

that is: $n_{Ps} k_v > 3.3$

- Plateau regime correct in our range of nPs
- Low k_v region and low nPs: σ scales as n^2......