New beam-preparation techniques for the CERN-AD experiment on Gravitational Behavior of Antimatter at Rest (GBAR)

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Overview

1. GBAR requirements
2. Positron accumulation technique
3. Antiproton decelerator

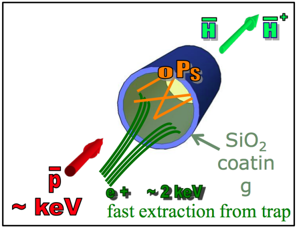
$\bar{\mathrm{H}}^{+}$ production

Goal : Measure g for WEP test using ultra cold antihydrogen (neV)
Method : Cooling using $\bar{\mathrm{H}}^{+}$ ions (Walz and Hänsch 2004)

$\bar{\mathrm{H}}^{+}$ production :

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

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

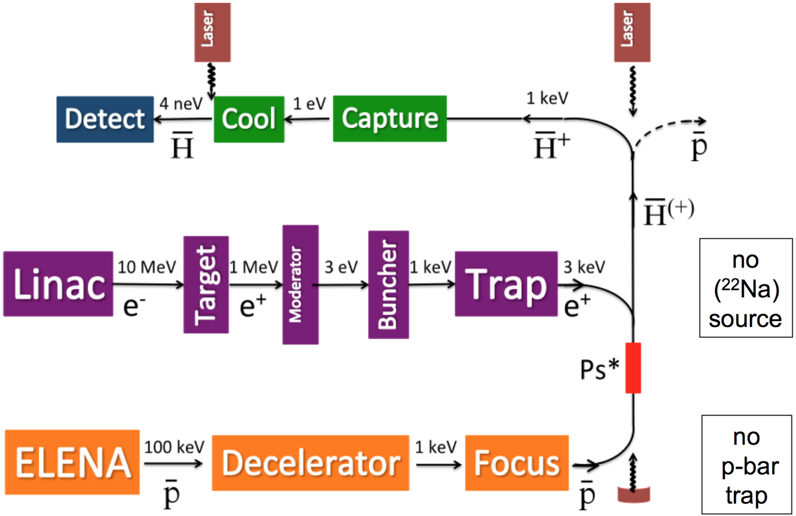


Requirements :

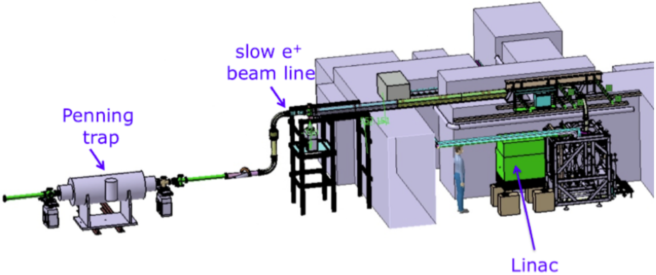
few 10^6 Antiprotons in the keV range
Dense Positronium cloud 10^{12} $\mathrm{Ps/cm^{-3}}$
$\Big\} \rightarrow$ $1 - 3\ \bar{\mathrm{H}}^{+}$, $10^4\ \bar{\mathrm{H}}$

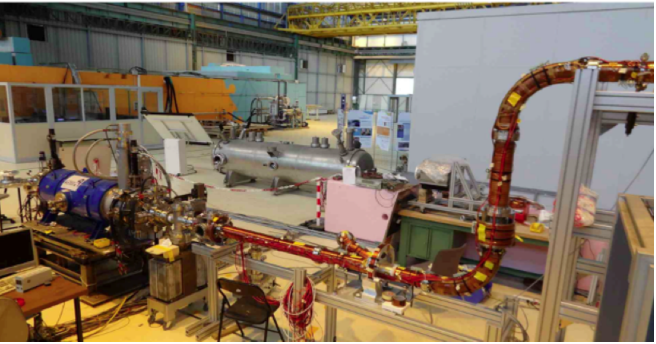
Ps cloud produced with a positron-Ps converter ($\varepsilon \sim$40%) $\rightarrow$ few 10^{10} e^{+}

GBAR schematic



e^+/Ps demonstrator in Saclay, France





- Electron LINAC :
  - 4.3 MeV / 200 Hz
  - 2.5 μs /120 μA
  - W meshes moderator
- Slow positron flux : 2 10^6 slow e^+/s
- Penning trap on beam line (from RIKEN)

Different accumulation techniques

Most efficient technique developed by C. M. Surko, improved by ATHENA collab. [1]

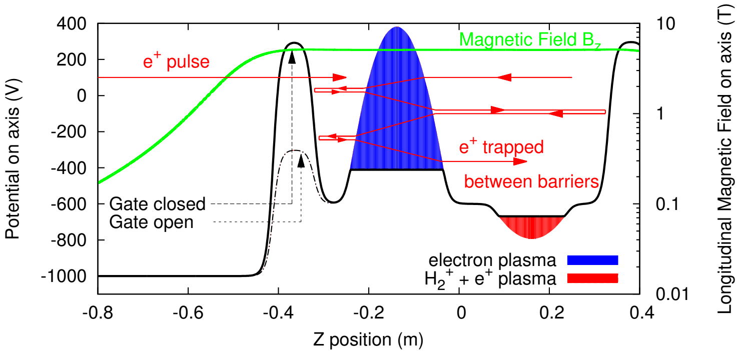
- Cooling in buffer gas trap + stacking in UHV Penning Trap
- Accumulation rate 7.6×10^3 e^+/s/mCi $\rightarrow \sim$4 % (with $\varepsilon_{mod,Ne}$=0.5%)
- Max : 1.2 10^9 e^+/2.5 hours

RIKEN Technique [2] $\rightarrow$ Ability to achieve higher efficiencies using a pulsed beam

- Cooling in UHV Penning Trap with a dense electron plasma
- Accumulation rate 3.6×10^2 e^+/s/mCi $\rightarrow \sim$0.2 % (with $\varepsilon_{mod,Ne}$=0.5%)
- Max : 10^6 e^+/100 s

[1] L. V. Jørgensen et al., Phys. Rev. Lett. 95, 025002 (2005)
[2] N. Oshima et al., Phys. Rev. Lett. 93, 195001 (2004)

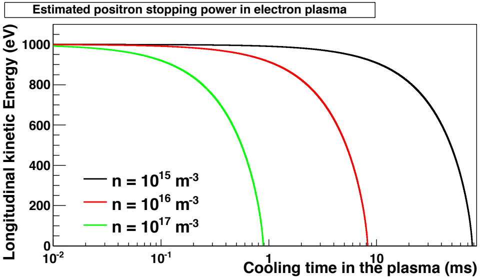
RIKEN technique, with pulsed beam



1. Acceleration at the entrance of the trap (Magnetic Mirror)
2. Confinement between potential barriers before the 1st roundtrip (pulse time-width $<$ 100 ns)
3. Cooling with e$^-$ plasma (time of cooling $<$ 1/beam frequency)
4. Cooling with H_2^+ and e$^+$

RIKEN technique, with pulsed beam

Coulomb-collisional damping in e^- plasma (D. V. Sivukhin, 1966) :



With $n = 10^{17}$ m^{-3} ($\sim 10^{10}$ e$^-$), Cooling time in the plasma < 1 ms

Further simulations :

- Kinetic energy distribution after the magnetic mirror
- e^- plasma : Maxwell Boltzmann distribution
- Potential distribution (TOF)

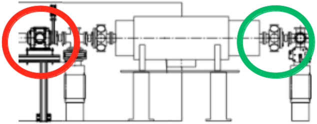
$\rightarrow$ max. cooling time ~ 3 ms

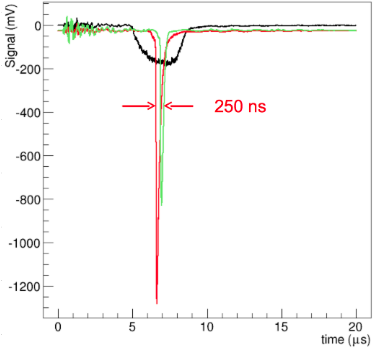
The e^+ pulse is sufficiently slowed to be kept in the trap during the injection of the next pulse, which guarantees the continuation of the cooling until its confinement in the second well. The trapping efficiency would only depend on the beam quality

Status at Saclay : Time Bunching of the e^+ pulse

$$\left.\begin{array}{l}\text{Pulse timewidth at the source } \sim 2.5\ \mu s \\ \text{Time of the first roundtrip } \sim 100\ \text{ns}\end{array}\right\} \rightarrow \text{ Time bunching}$$

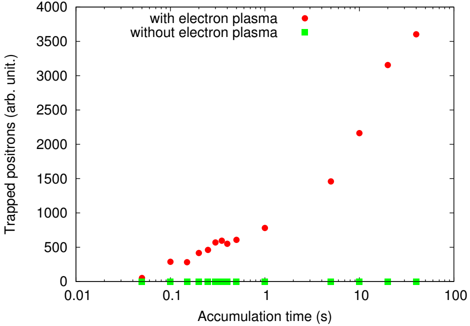
At the level of the source, the positrons are accelerated progressively with time in the burst to compensate their late production, focal point in the trap ($\sim$14 m away)





Status at Saclay : e^+ trapping

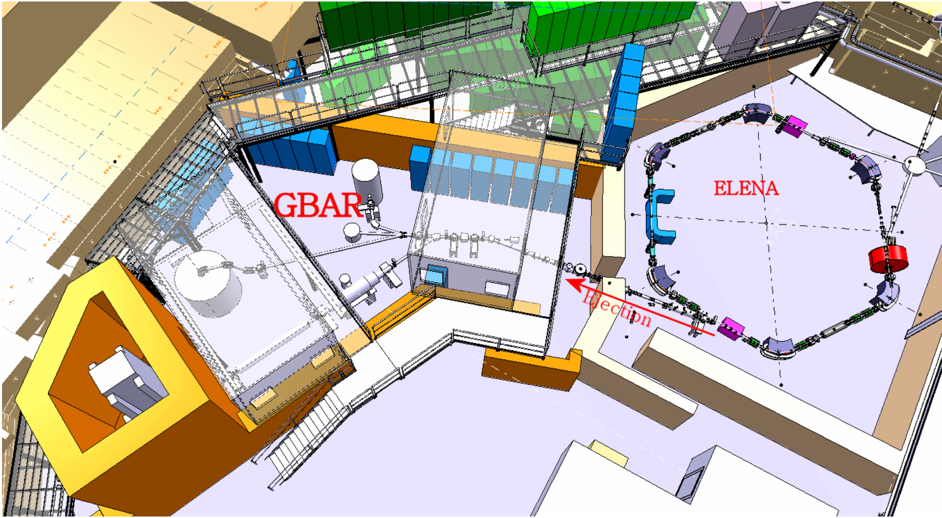
First results last month :



The principle has been demonstrated.

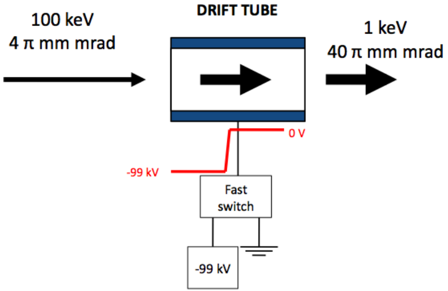
- Beginning of our investigations
- Setup is not complete yet

GBAR layout



GBAR antiproton decelerator

- Deceleration from 100 keV to 1 keV (Ps 3d), 2 keV (Ps 2p) , 6 keV (Ps 1s or 3d)
- Method : $\bar{p}$ pulses are directly decelerated and injected in reaction chamber
- ELENA beam [3] : 100 keV, 4π mm mrad, $\Delta p/p = 2.5\ 10^{-3}$ (95%), 300 ns

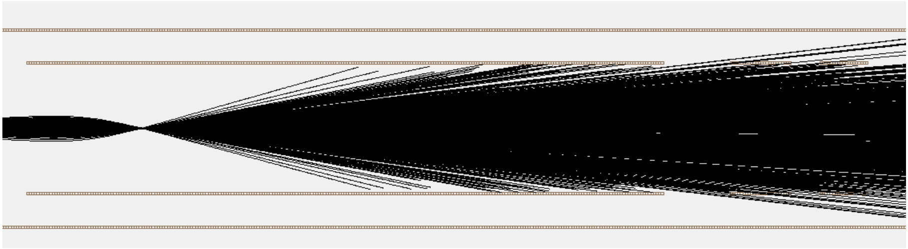


Pulsed drift tube used at ISOLDE and with many Trap setup
ISOLTRAP : rise time of 100 ns for ∼60 kV

[3] Progress in ELENA design, IPAC 13

GBAR antiproton decelerator, SIMION simulation

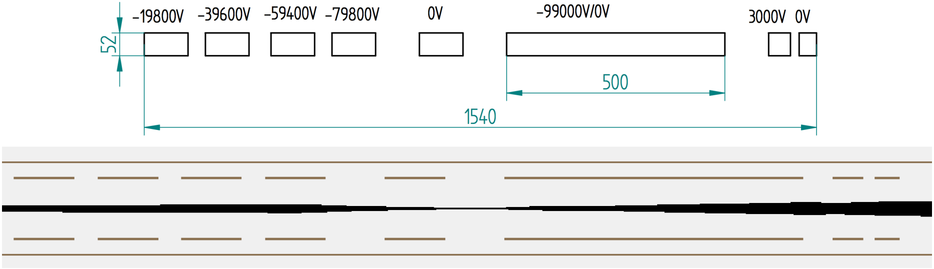
Only a drift tube, length 500 mm, inner radius 50 mm



→ The $\bar{p}$ beam blows up in the drift tube

GBAR antiproton decelerator, SIMION simulation

Add a set of multistage deceleration electrodes before the drift tube to avoid the focusing effect at the entrance



GBAR antiproton decelerator, SIMION simulation

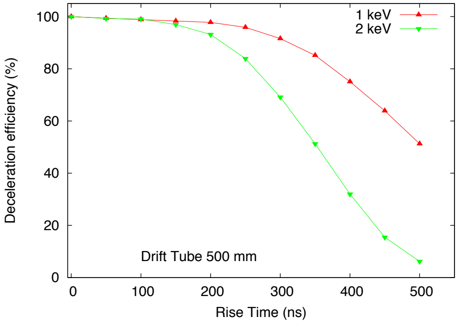
Emittance after DT :

1 keV $\varepsilon = 43\ \pi$ mm mrad (95%)

2 keV $\varepsilon = 30\ \pi$ mm mrad (95%)

6 keV $\varepsilon = 19\ \pi$ mm mrad (95%)

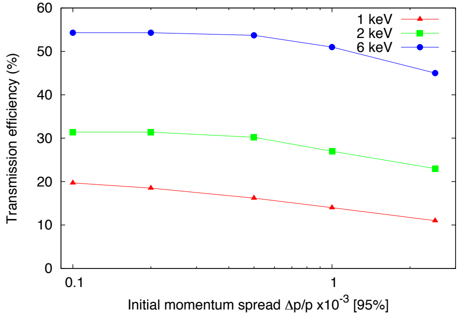
6kV : DT -98 kV $\rightarrow$ -4 kV



For a rise time of 200 ns, deceleration efficiency $> 90\%$ and emittance close to the expected value

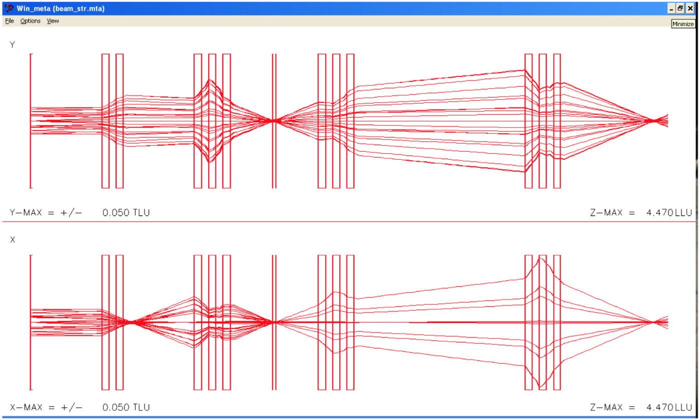
GBAR antiproton decelerator, SIMION simulation

Injection of $\bar{p}$ in reaction chamber L= 2cm , R=0.5 mm
$\rightarrow$ Focusing optics required.
First scheme : Einzel lens



GBAR antiproton decelerator, GIOS simulation

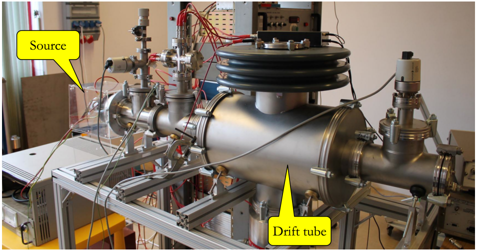
Further simulations in progress (doublet + triplet of quadrupoles) + Transport of $\bar{\mathrm{H}}^+$

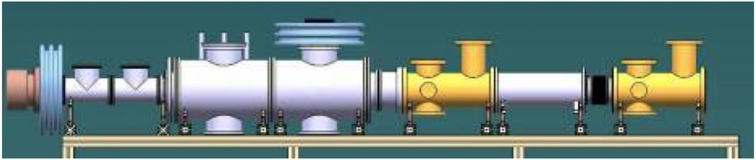


Transmission efficiency ∼35 %

GBAR antiproton decelerator, status at Orsay

Decelerator test-bench under construction at Orsay





- 5keV beam 1 μA CW
- New HV platform for 100 kV, design of the electrodes and the drift tube, design of the HV fast switch for the drift tube.

Conclusion

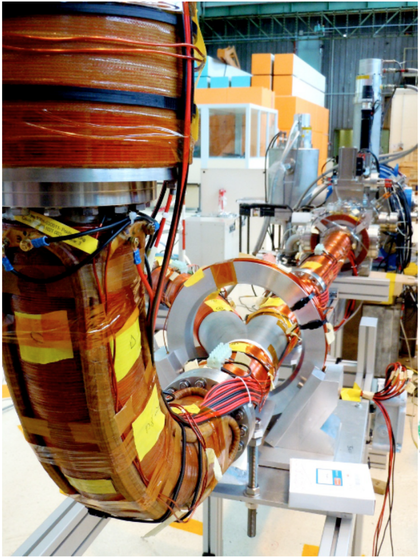
Positrons :

- Slow positron pulsed source is running at Saclay (flux comparable with ^{22}Na source)
- Principle of accumulation with a pulsed beam has been demonstrated

Antiprotons :

- Results of drift tube simulations are promising
- Simulation of the optics in progress
- Prototype under construction

Thank you for your attention



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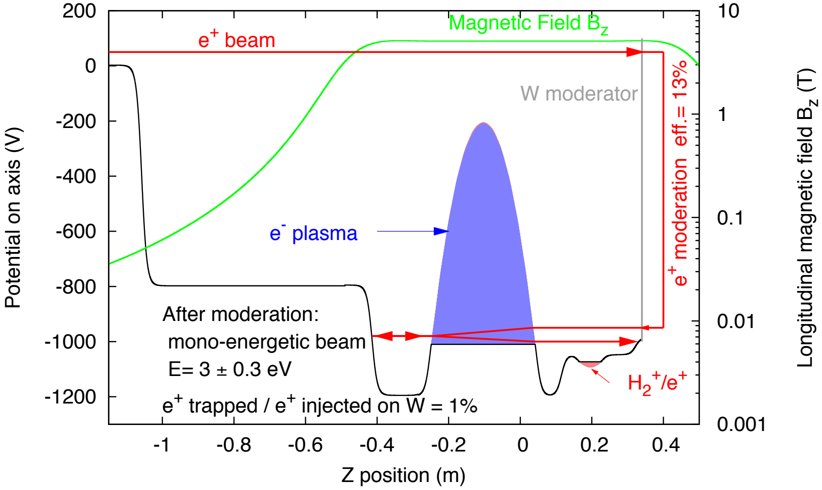
RIKEN technique



electron density $n \sim 10^{17}\ \text{m}^{-3}$

GBAR Proposal

Electrons						
Linac frequency	Mean current	Pulse current	Pulse duration	Electrons per pulse	Electron rate (s^{-1})	
300 Hz	0.2 mA	0.33 A	2 µs	4.2×10^{12}	1.25×10^{15}	
Positrons						
Production efficiency (at 10 MeV)	Transport efficiency	Fast positrons per pulse	Fast positron rate (s^{-1})	Moderation efficiency	Slow positrons per pulse	Slow positron rate (s^{-1})
5.5×10^{-4}	80 %	1.8×10^{9}	5.5×10^{11}	5×10^{-4}	9.2×10^{5}	2.8×10^{8}
Positron storage						
Trapping efficiency	Injection time	Stored positrons				
70 %	110 s	2.1×10^{10}				
Positronium						
Production efficiency	Tube section	Tube length	Positronium density	Loss fraction from Ps decay		
35 %	1 mm^2	1 cm	7.4×10^{11} cm^{-3}	0.5		
Antihydrogen positive ions						
Antiprotons per pulse	Deceleration and bunching efficiency	Production cross section of the $\overline{H}$ atom	Production cross section of the $\overline{H}^+$ ion	$\overline{H}$ per pulse	$\overline{H}^+$ per pulse	
6×10^{6}	80 %	4.4 10^{-16} cm^2	8.8 10^{-15} cm^2	3.9×10^{2}	0.32	
Antihydrogen atoms						
$\overline{H}^+$ Trapping efficiency	Cooling efficiency	cold $\overline{H}^+$ per pulse	Photodetachment efficiency	Detector acceptance	$\overline{H}$ events per pulse	$\overline{H}$ event rate (s^{-1})
100 %	70 %	0.2	99 %	65 %	0.14	1.3×10^{-3}

Table 1: Expected efficiencies and performances.

New estimation with 20 MeV linac : slow positron flux 1.5 10^8 e^+/s

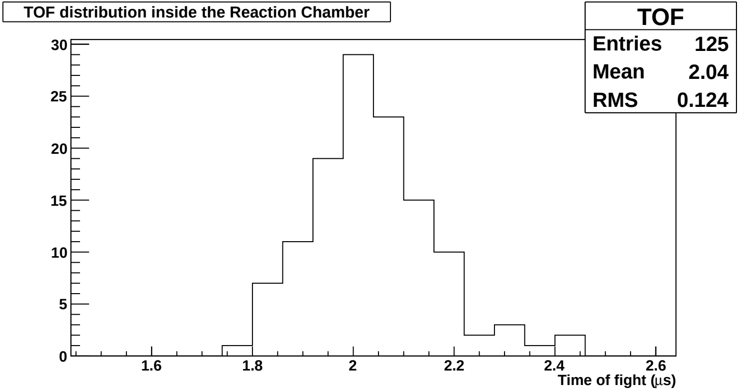
Electron plasma parameters

TABLE 1. Electron plasma parameters.

Parameter	symbol	value
electron number	N	9×10^9
density (r=0)	n	$\sim 10^{17}$ m^{-3}
temperature	T	$\sim$0.53 eV
radius	r_p	$\sim$400 μm
half-length	z_p	$\sim$11 cm
cyclotron pulsation	ω_c	8.8×10^{11} rad.s^{-1}
plasma pulsation	ω_p	$\sim 2 \times 10^{10}$ rad.s^{-1}
bounce pulsation	ω_z	1.6×10^8 rad.s^{-1}
rigid-rotation pulsation	ω_r	$\sim 2.3 \times 10^8$ rad.s^{-1}
Debye length	λ_D	$\sim$17 μm
cyclotron radius	r_c	$\sim$340 nm
classical distance of closest approach	b	$\sim$3 nm
Lifetime (without heating)	τ_e	$\sim$6000 s

TOF in the reaction chamber

$\Delta p/p = 2.5\ 10^{-3}$, 1keV deceleration 1 Einzel lens



Time of cooling of different e^+ beam radius