New positron trapping scheme for GBAR experiment

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Overview

1. Positrons requirement
2. RIKEN accumulation technique
3. Positron accumulation with a pulsed beam

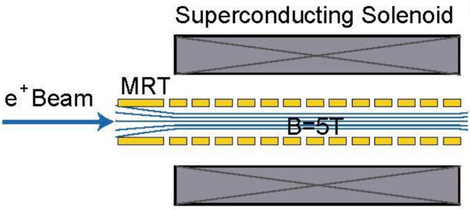
Positronium target production

- $\bar{\mathrm{H}}^+$ production uses a positronium cloud (Ps $[\mathrm{e}^+\mathrm{e}^-]$)
- Ps cloud with a density $10^{12}\ \mathrm{Ps/cm^{-3}}$
- Ps cloud is created with a $\mathrm{e}^+ \rightarrow \mathrm{Ps}$ converter ($\epsilon \sim 40\%$)
  → Requires a pulse of few 10^{10} e$^+$, with a timewidth less than $\tau_{Ps} = 142$ ns

Slow e$^+$ source : highest flux ~10^9 e$^+$/s → Positron accumulation in a Penning-Malmberg trap

Penning-Malmberg trap

Electromagnetic trap, axisymmetric shape. Confined positrons behave as a non neutral plasma.



Dimensions :
$\sim$ 23 electrodes
$R_{elec} = 2$ cm
$L_{elec} = 2$ cm

Radial confinement

Uniform magnetic field along the trap axis, $B_z = 5$ T

Axial Confinement

Harmonic potential well produced by cylindrical electrodes

$\phi^{ext}(r, z) = A\left(2z^2 - r^2\right)$

Different accumulation techniques

- Slow positron (eV) accumulation from a continuous beam.
- Radioactive β^+ source : ^{22}Na coupled with a Neon moderator $\varepsilon_{mod} \sim 0.5$ % ($\sim$500 keV $\rightarrow$ eV)

Accumulation technique	Accumulation rate (e^+/s/mCi)		Max amount of e^+
RIKEN (Oshima et al.)	3.6×10^2	$\sim$0.2 %	10^6
ATHENA (Jørgensen et al.)	7.6×10^3	$\sim$4 %	10^9

RIKEN method is able to reach high accumulation efficiencies using a e^+ pulsed beam

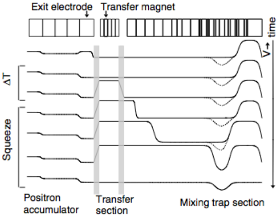
Accumulation techniques comparison

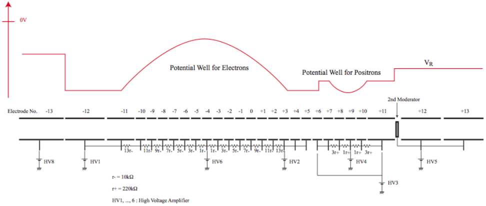
ATHENA

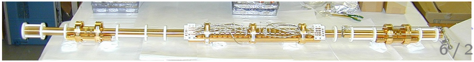
- Two traps
- Positron cooling in the first trap with a buffer gas
- Positron lifetime ∼ 100 s
- Injection in the second trap (UHV)

RIKEN

- Only one trap
- e^+ moderation with a tungsten cristal (reflexion mode)
- e^+ cooling in an electron plasma and H_2^+ plasma by Coulomb interaction.

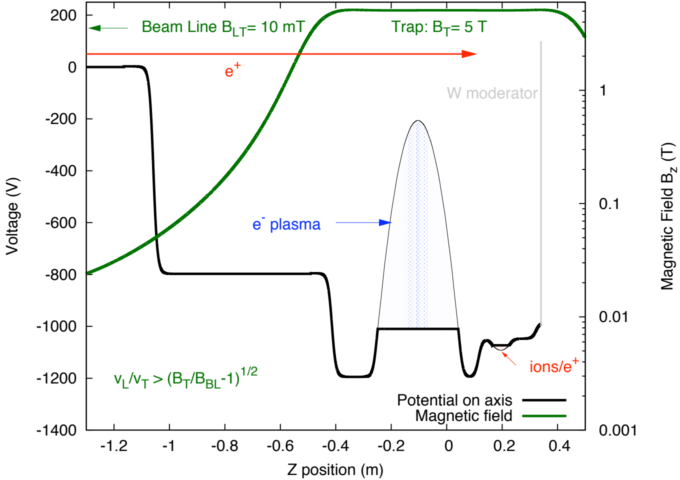






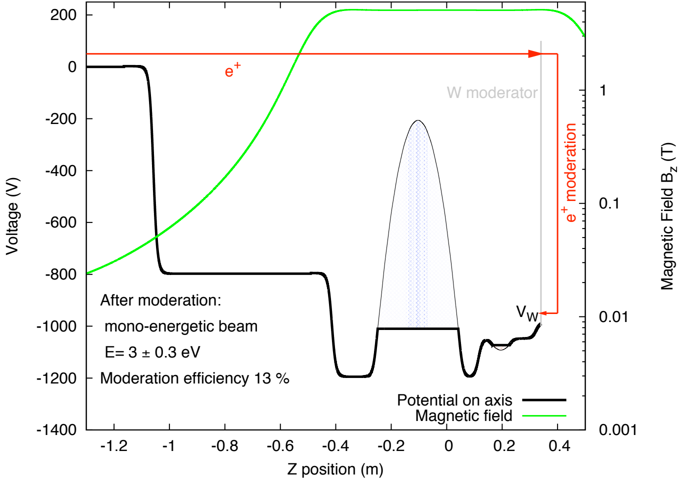
RIKEN accumulation technique :

Positron injection in the trap :



RIKEN accumulation technique :

Positron moderation with W cristal :



After moderation:

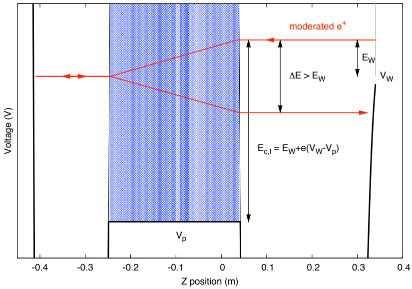
mono-energetic beam

E= 3 ± 0.3 eV

Moderation efficiency 13 %

RIKEN accumulation technique :

Positron cooling in the electron plasma by
Coulomb collisionnal damping



ΔE depends on :

- the electron plasma density n
- the distance travelled by e^+ in the electron plasma
- the kinetic energy of e^+ in the electron plasma
  $\rightarrow V_W - V_p$

Particle-plasma interaction

Coulomb collision of positrons in an electron plasma (M. A. Leontivich, K. Miyamoto) :

$$\frac{dv_{\parallel}}{dt} = -\frac{v_{\parallel}}{\tau_{coll,e}}$$

→ Collision time $\tau_{coll,e}$:

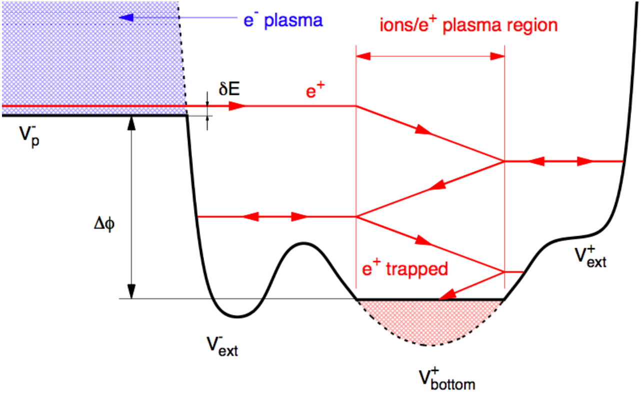
$$\tau_{coll,e} = \frac{8\pi\varepsilon_0^2 \mu m v^3}{n e^4 \ln\Lambda} \text{ , } \mu \text{ reduce mass}$$

$$\ln\Lambda = \ln\left(\frac{\lambda_D}{b_{90}}\right) \text{ , } b_{90} = \frac{e^2}{4\pi\varepsilon_0}\frac{1}{mv^2} \text{ , } \lambda_D = \sqrt{\frac{\varepsilon_0 k_B T}{ne^2}}$$

Cooling until electron thermal velocity, T∼0.01 eV.

RIKEN accumulation technique :

Positron cooling in the H_2^+ cloud :



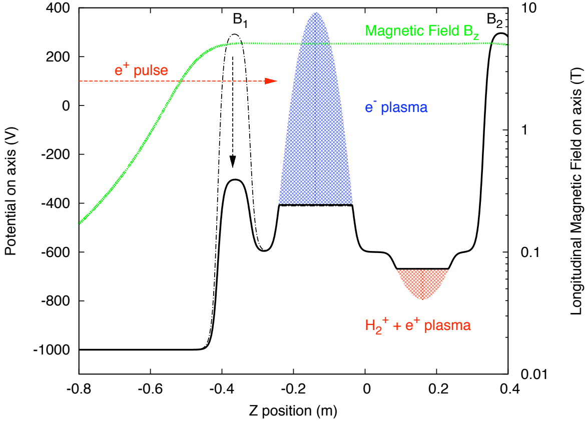
Confinement rate divided by 10 without ions

Upgrade of the RIKEN technique

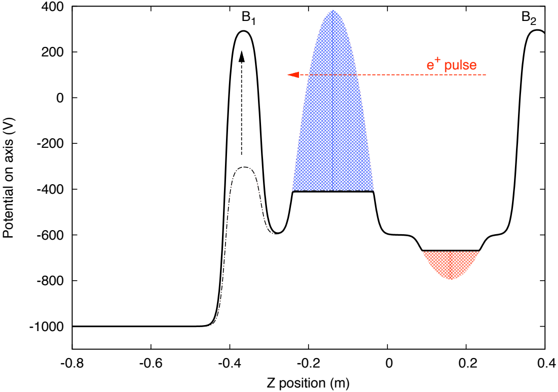
- Only one Penning-Malmberg trap
- Slow positron pulsed beam (SACLAY prototype : 200 Hz, timewidth : 4 μs)
- Tungsten moderator removed

- Positrons are accumulated pulse by pulse
- Positron pulses are confined between two potentiel barriers B_1 et B_2 in the 5T region
- Positron cooling by Coulomb collisionnal damping in an electron plasma

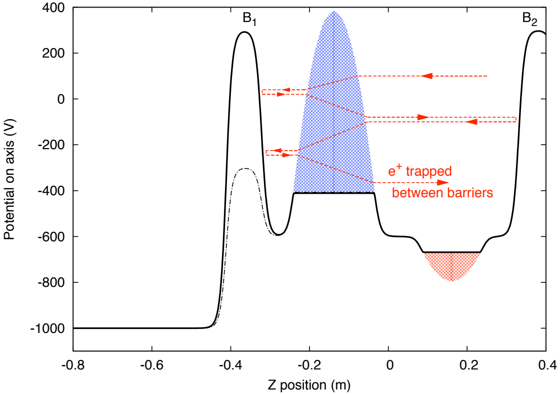
B_1 is lowered during positron injection



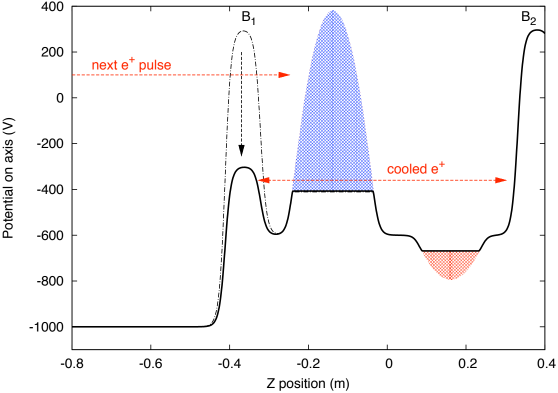
B_1 is rised up before the first roundtrip of the pulse
time of first round trip ~100 ns → time bunching of e^+ pulses



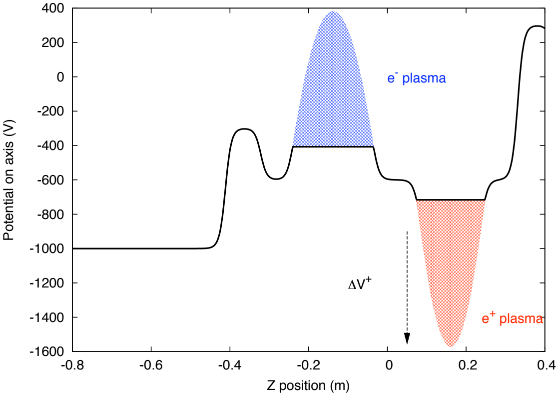
Positrons are cooled down by Coulomb collisionnal damping during their several roundtrips in the electron plasma



Positrons have to be cooled down enough before opening B_1 for the injection of the next pulse



The depth of the second well is increased during positron accumulation, until ∼1000 V for $\sim 10^{10}$ e^+



Overall efficiency

The overall trapping efficiency can be divided in 3 efficiencies :

- Transport efficiency in the magnetic mirror :

$$\rightarrow \varepsilon_t = \frac{\text{number of } \mathrm{e}^+ \text{ reaching the trap region}}{\text{number of } \mathrm{e}^+ \text{ in the bunch}}$$

- Bunching efficiency :

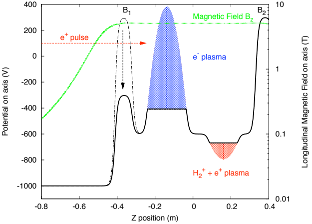
$$\rightarrow \varepsilon_b = \frac{\text{number of } \mathrm{e}^+ \text{ confined in the trap region once the gate is raised}}{\text{number of } \mathrm{e}^+ \text{ reaching the trap region}}$$

- Cooling efficiency :

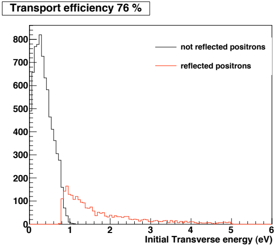
$$\rightarrow \varepsilon_c = \frac{\text{number of } \mathrm{e}^+ \text{ cooled down enough when } \mathrm{B}_1 \text{ is lowered}}{\text{number of } \mathrm{e}^+ \text{ confined in the trap region once the gate is raised}}$$

Transport efficiency ε_t

- reflexion in the magnetic field gradient if $\frac{E_\perp}{E_\parallel} > \frac{B_L = 10\text{mT}}{B_T = 5\text{T}}$
- reflexion at the level of the potential barrier B_1 in the magnetic field gradient : $V_b = -300$ V
- $\varepsilon_t = 76\%$



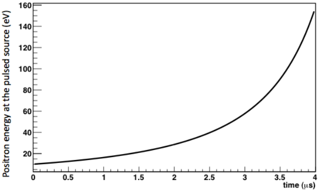
Transport efficiency strongly depends on the transverse energy of positrons ($E_\parallel \sim$1 keV)

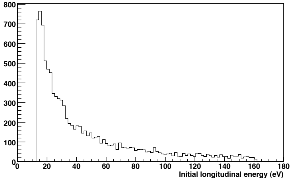


Bunching efficiency ε_b

$$\left.\begin{array}{l}\text{Pulse timewidth at the source} \sim 4\ \mu\text{s} \\ \text{Time of the first roundtrip} \sim 100\ \text{ns}\end{array}\right\} \rightarrow \text{Time bunching}$$

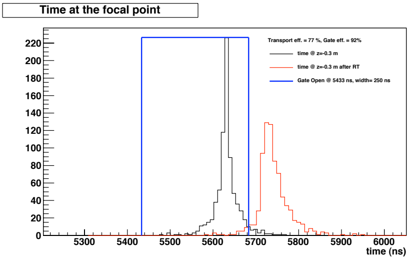
At the level of the source, the positrons are accelerated progressively with time in the burst to compensate for their late production.

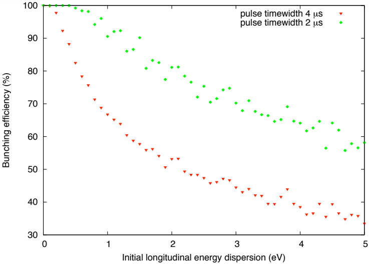




Time bunching is effective at a focal point behind B_1

Bunching efficiency ε_b

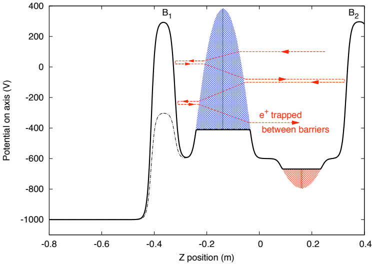




- $\varepsilon = 92\%$ with the Saclay bunching method ($\sigma_{E_{\|}}$=0.3 eV)
- Bunching efficiency strongly depends on the longitudinal energy spread
- Bunching method for Saclay needs a long distance between the source and the trap (L>10 m), it seems incompatible with our place in the AD facility.

Cooling efficiency ε_c

The confinement time t_C is the time to cool down a positron until its confinement between the two potential barriers, when the B_1 is lowered ($V_b = -300$ V)
→ time when $E_{||} < e(V_b - V_p(r))$ in the electron plasma
→ Maximal t_c defines the injection frequency



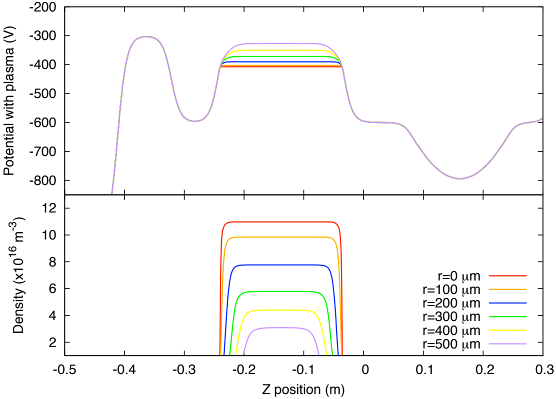
t_C depends on :

- the electron plasma parameters (density, dimension, temperature)
- the difference between V_b and the potential in the plasma $V_p(r)$
- the initial energies $(E_{||}, E_{\perp})$ in the plasma
- the time of each roundtrip
- the effective time in the electron plasma during each roundtrip
- the r position of the positron (V_p and n depend on r!)

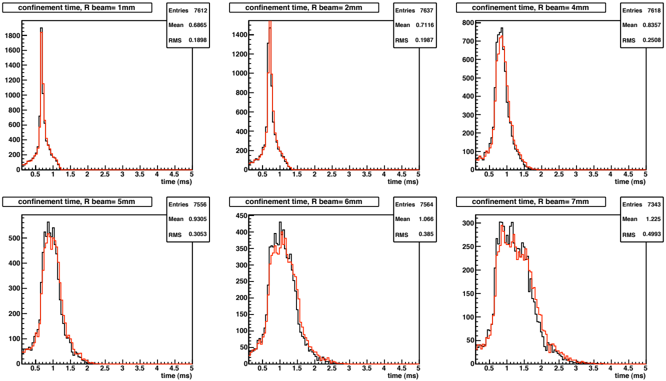
Electron plasma parameters

Parameter	symbol	value
electron number	N	9×10^9
density (r=0)	n	$\sim 10^{17}$ m^{-3}
temperature	T	$\sim$0.01 eV
Debye length	λ_D	$\sim$2 μm
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}

Electron plasma configuration



t_C distribution in function of beam radius in the beam line



Cooling efficiency = 100 % if the beam radius R<7 mm and a source frequency < 300 Hz

Conclusion

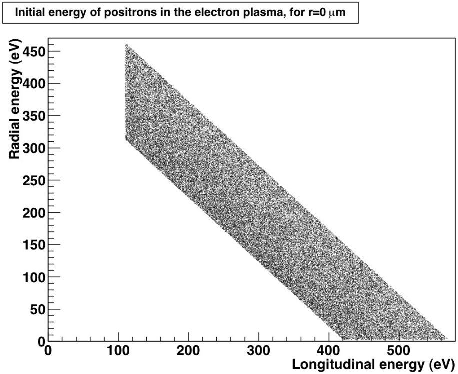
Overall efficiency $\sim$ 70%, it only depends on :

- the transverse energy of the beam (positron losses in the magnetic field gradient)
- the longitudinal energy spread of the beam (Saclay bunching method)

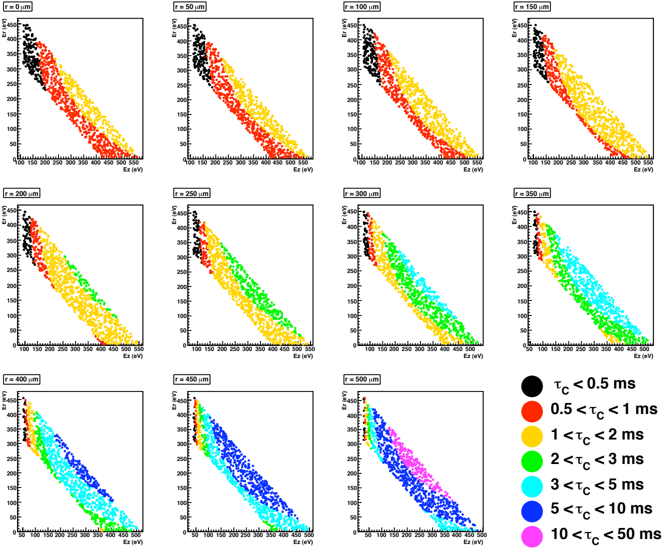
The positron flux is expected to be 2.8×10^8 $e^+.s^{-1}$. With this flux, the accumulation time of 2×10^{10} e^+ would be $\sim$100 s, i.e. the time between two ELENA $\bar{p}$ pulses

Initial energies ($E_\parallel, E_\perp$) in the electron plasma

Considering a positron not reflected, its total energy at the level of the first potential barrier, i.e. behind the magnetic mirror, is $E_{z,ini} - eV_{gate}$. Its longitudinal energy is spread from $\sim$ 0 eV to $E_{z,ini} - eV_{gate}$ because of the magnetic gradient at the entrance of the trap. In the electron plasma, its longitudinal energy is then increased by $-e(V_p(r) - V_{gate})$



τ_C versus initial $(E_\parallel, E_\perp)$ and r



Efficacité d'entrée dans le piège

Conditions initiales : pulse dans la ligne de transport (B=10mT), diamètre du pulse 5 mm, énergie : $\langle E_\perp \rangle = 0.7$ eV, $E_{||} = 50$ eV