Efficient positron trapping at a linac based positron source using a silicon carbide remoderator

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on behalf of the GBAR collaboration

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ppc 12.5

Outline

- The GBAR project and its positron line
- Buffer gas trap in the linac-based positron line
- Why use a remoderator?
- Changes in the trapping scheme
- Test setup and new trapping sequence
- Performance of the SiC moderator based setup
- Conclusions and outlook

The GBAR experiment at CERN

- Test of the weak equivalence principle with antihydrogen
- Aim: gravitational free fall of antihydrogen with 1 % precision
- ~10 µK is needed (~0.5 m/s)

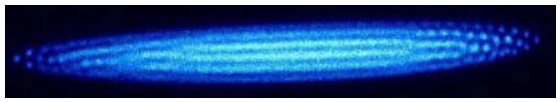
$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$
$$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$$

Cooling of neutrals to this temperature is not possible

Distinctive idea: use positive antihydrogen ion, created by two reactions in a positronium cloud

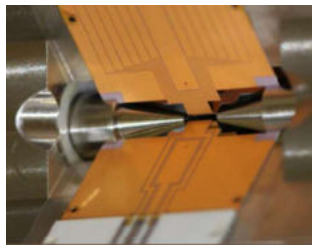
$\bar{H}^+$

Doppler sympathetic cooling (Paul trap)



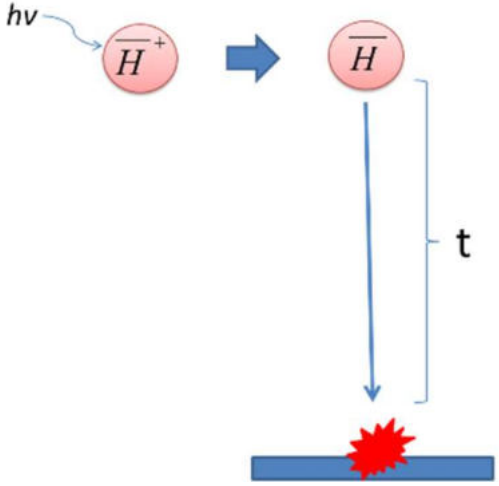
Be^+ ($+ D^+$) crystal

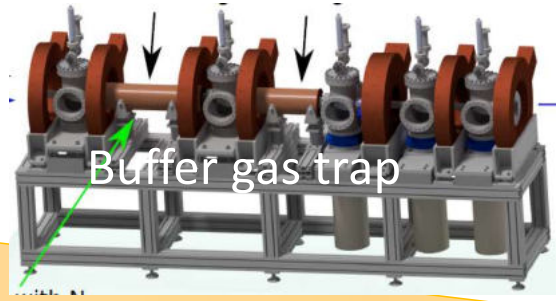
Raman sideband cooling (precision trap)



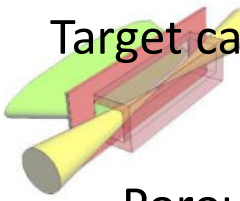
Be^+ - $\bar{H}^+$

Photodetachment + free fall

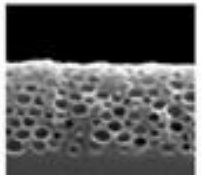




Target cavity



Porous SiO_2



Positron pulse
~keV

Ps (~50 meV)
+ pbar (~keV)
reaction

Antiproton trap
(in development)

~keV

Antiproton pulse

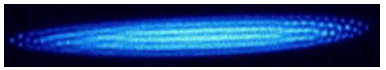
keV

eV

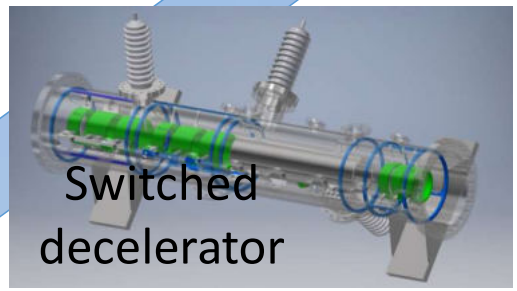
meV

$\overline{H}^+$

Capture trap



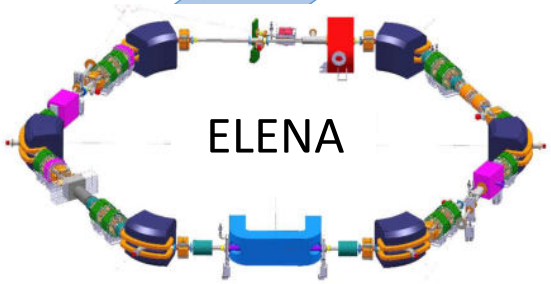
Doppler sympathetic
cooling (Paul trap)



100 keV
Cycle: 108 s

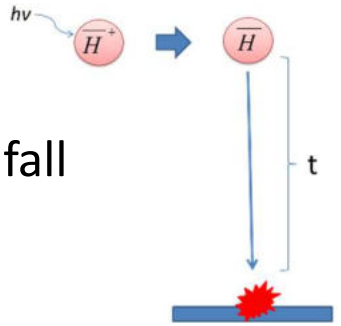
Raman
sideband
cooling

10 µeV

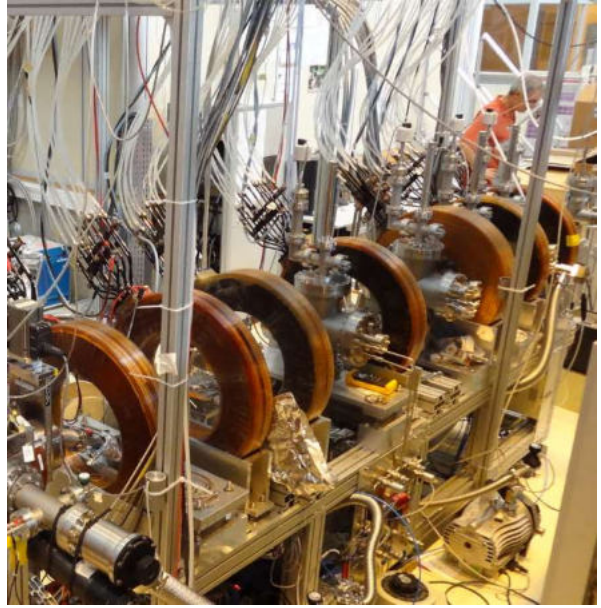


(100 keV antiproton)

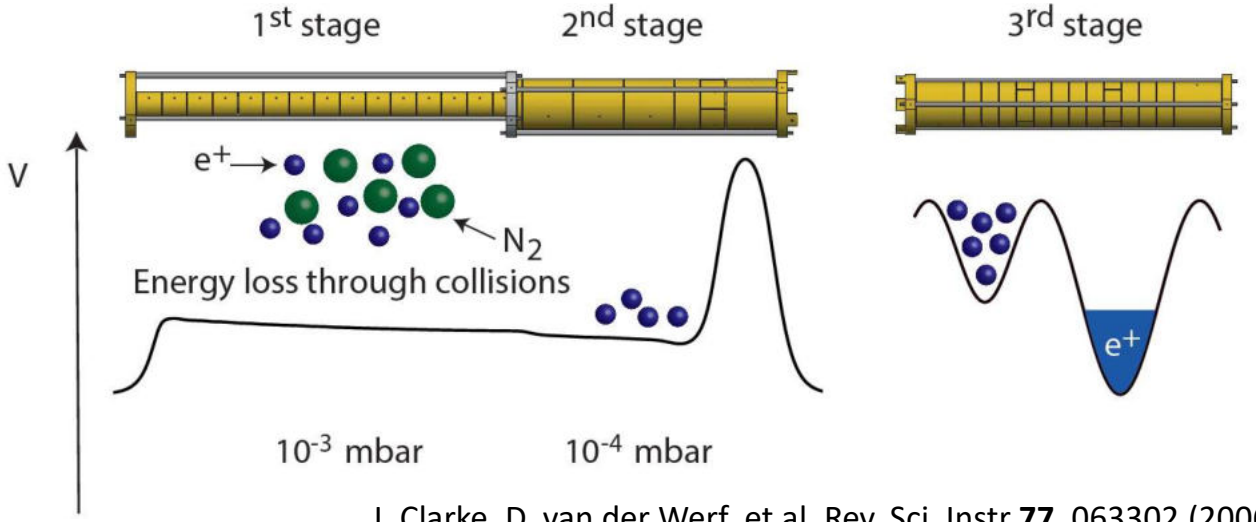
Photodetachment + free fall



Buffer gas trap at the CERN GBAR line



- Buffer gas trap (BGT) or « Surko trap » to capture and trap moderated e^+
- Nitrogen (1st stage) + CO_2 (2^{nd} stage)



J. Clarke, D. van der Werf et al, Rev. Sci. Instr **77**, 063302 (2006)

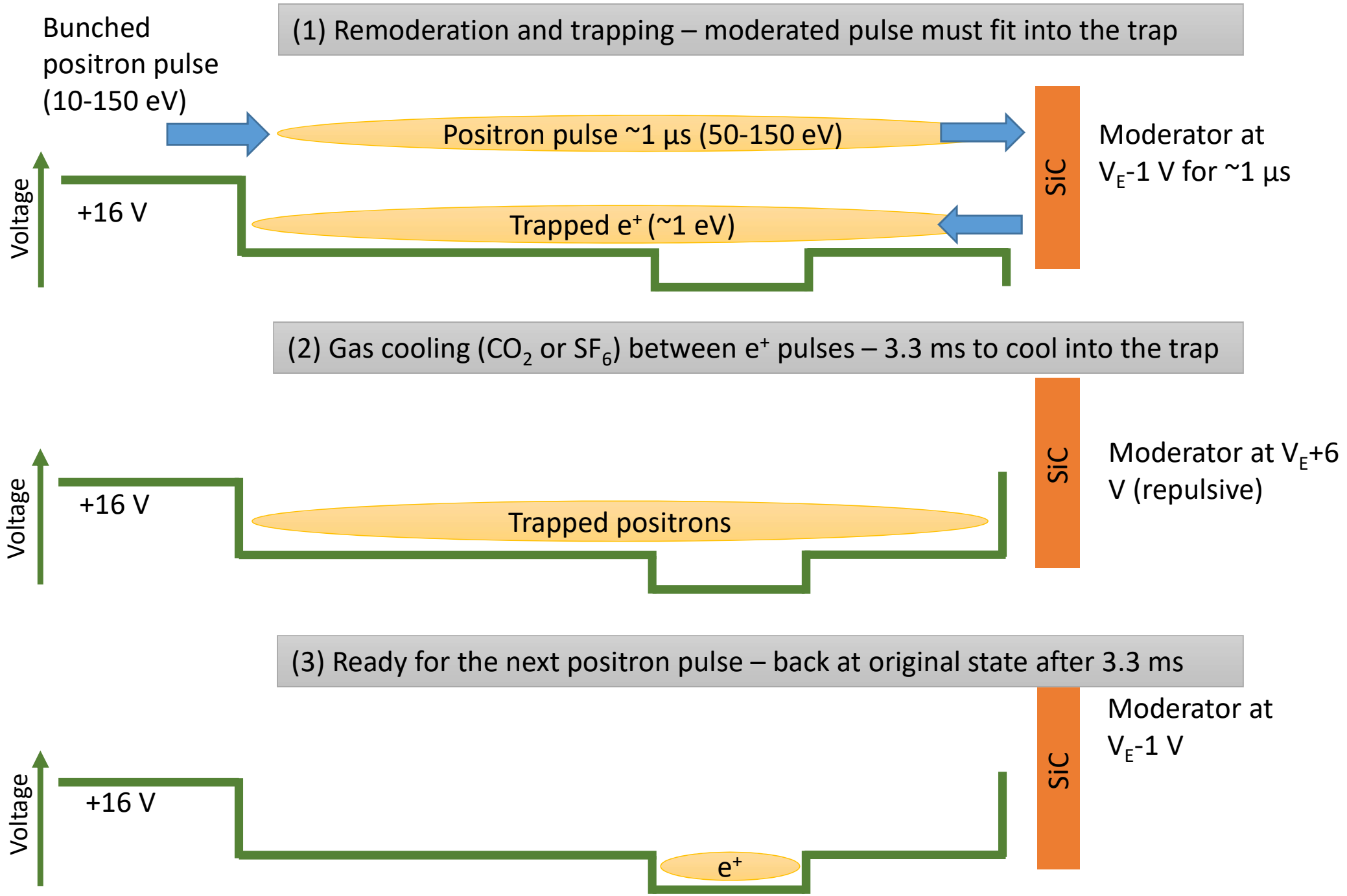
Can we replace the first stage with a remoderator?

- First stage of a BGT: significant energy loss in one collision with N_2
- Effect of a remoderator: significant energy loss

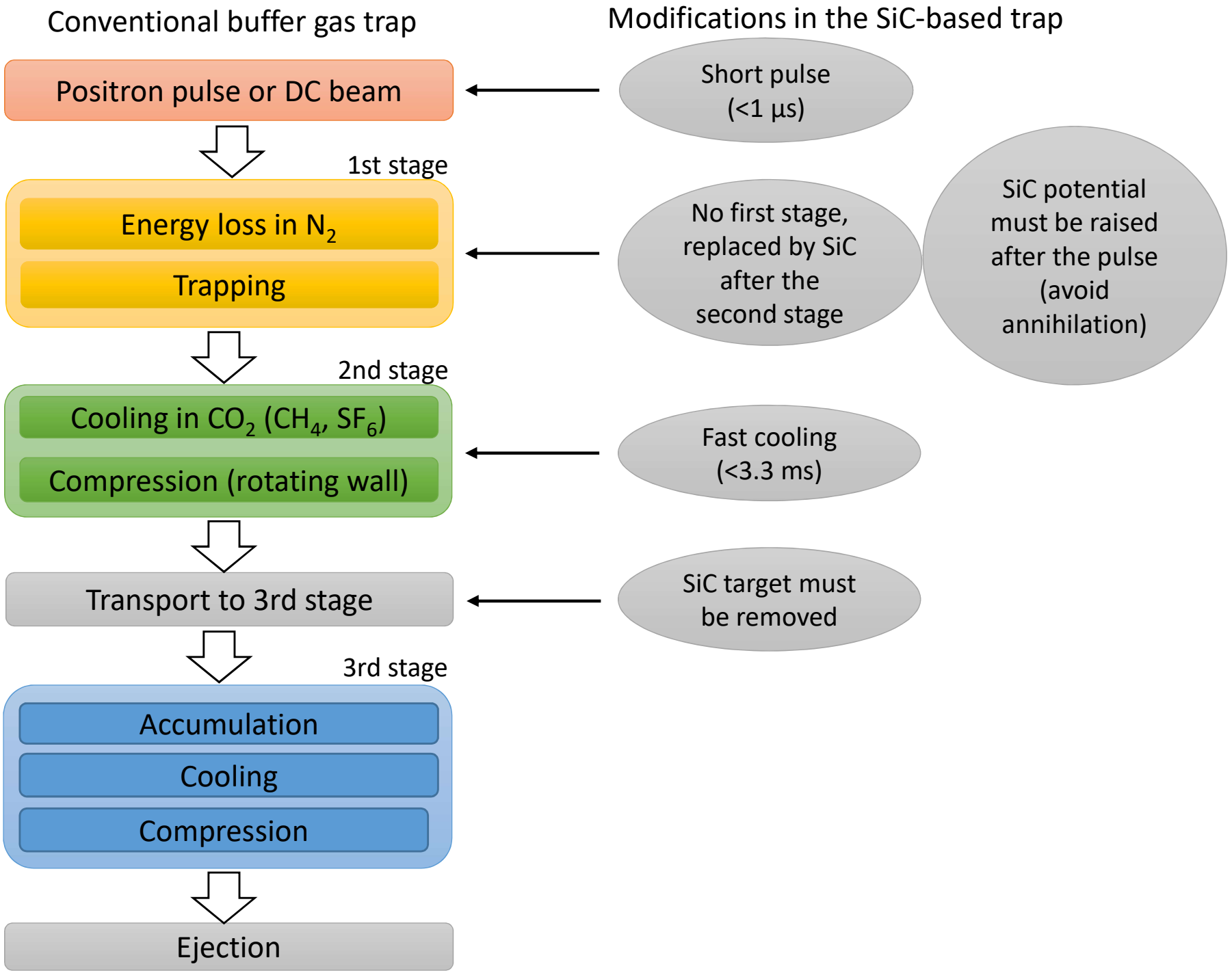
} Similar effect!

- Advantages:
  - may work better with the broad energy distribution of the linac source
  - avoid second gas line

The new trapping sequence

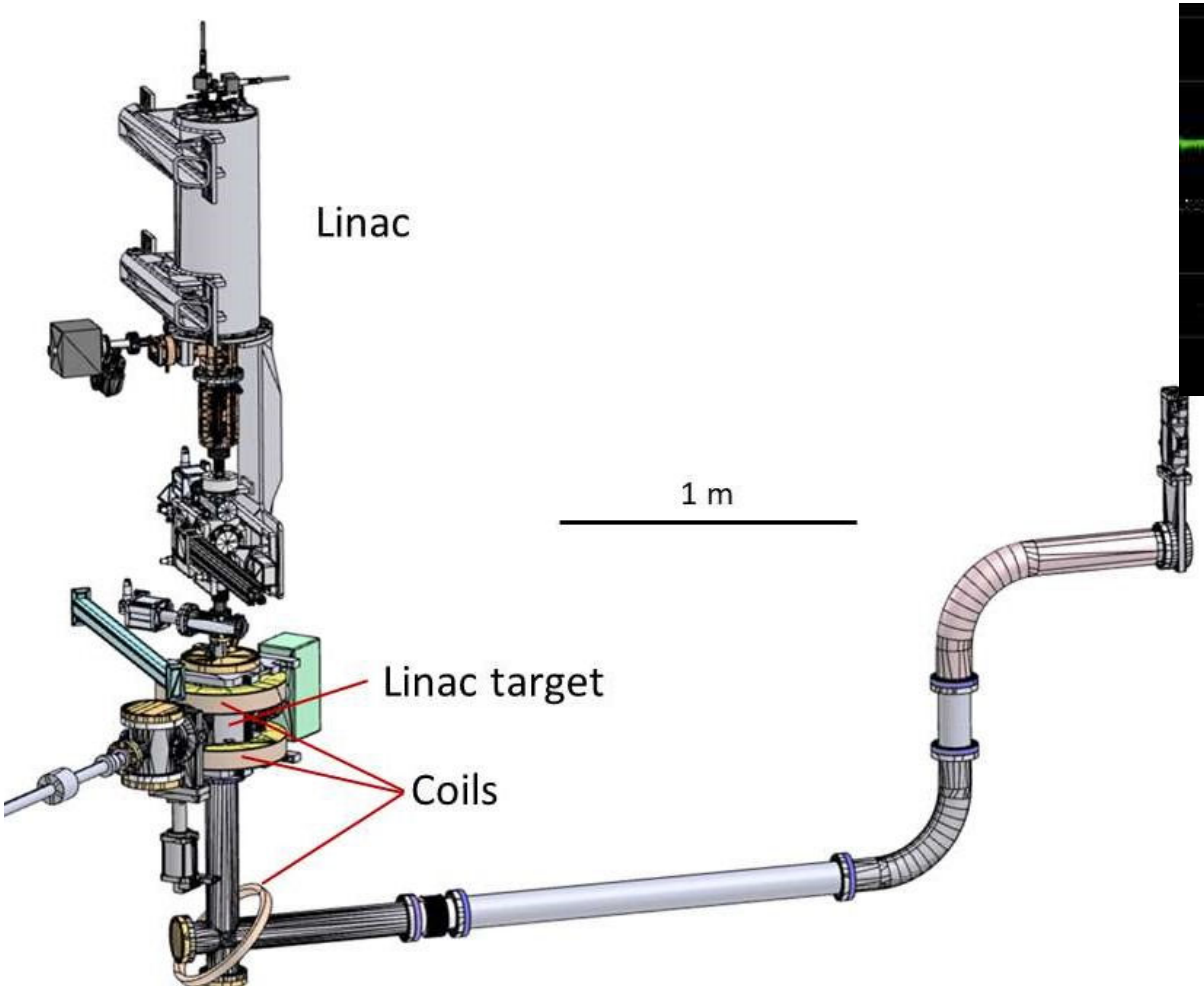


Changes in the trapping scheme



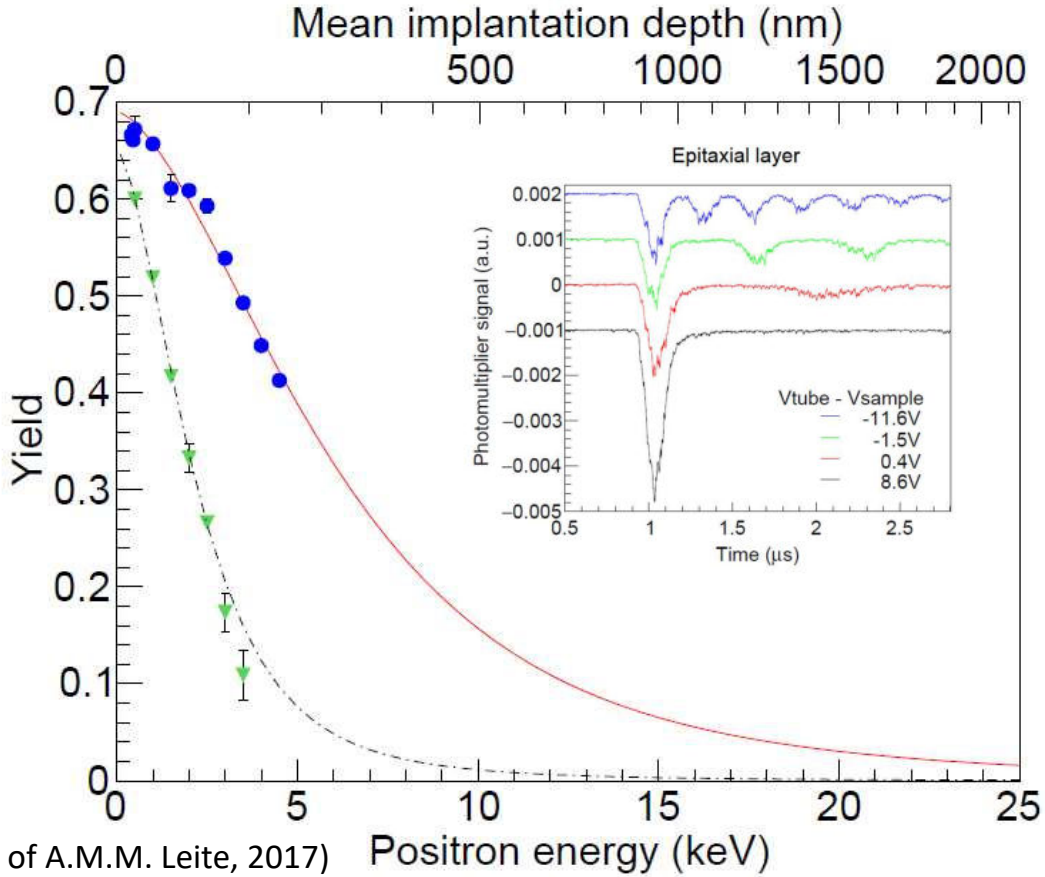
Short positron pulse

- Linac-based source:
  2.85 µs long pulses with max. 300 Hz
  (3.3 ms repetition time)
- Long beamline (>8 m)
- Buncher pulse on the moderator to compress positron pulse



Efficiency of SiC remoderation

- Very robust moderator, works in poor vacuum
- Contradictory numbers in the literature
  30 % or > 60 % moderation efficiency?
- No study with very low positron energy
- Our previous studies have given > 60 %
- This study confirms this number at low positron energy
- Low energy: significant epithermal emission
  may be usable for trapping



(Thesis of A.M.M. Leite, 2017)

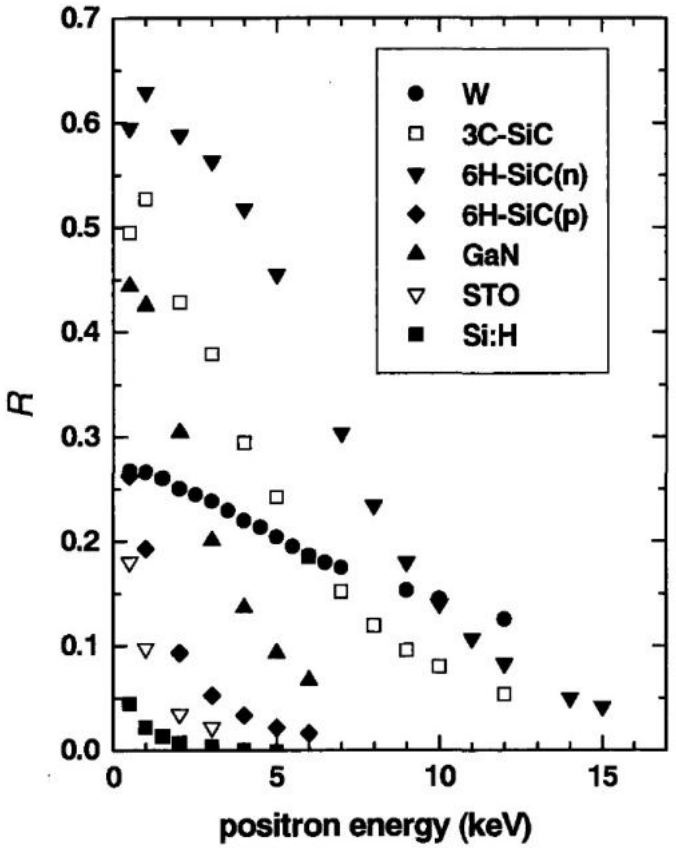


Fig. 3. Re-emitted positron ratio R as a function of positron energy for tungsten, 3C–SiC, n-type 6H–SiC, p-type 6H–SiC, $SrTiO_3$, and Si:H.

Suzuki et al, Jpn. J. Appl. Phys. 37,4636(1998)

SIC: epithermal emission?

- Positron work function: -2.1 V
- Rather broad energy distribution
- Remoderator must work at <~50-200 eV energy
- Low energy: significant epithermal emission
- No studies at low energy
- Epithermal fraction can be still usable for trapping

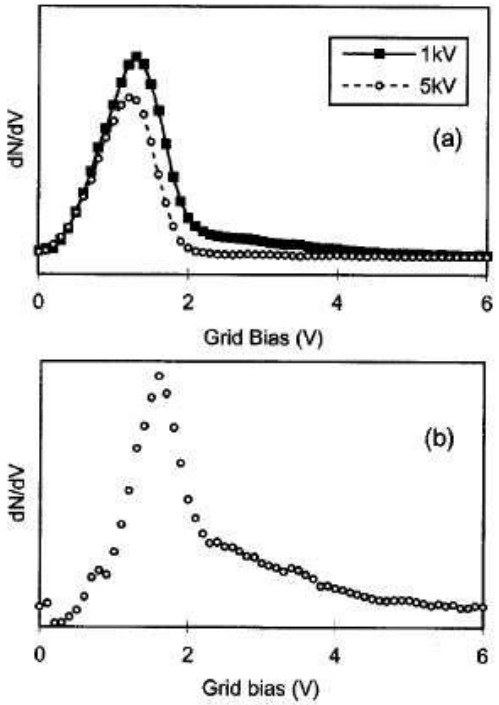


FIG. 5. (a) Energy distributions of reemitted positrons from SiC sample at 1 and 5 keV incident energies. The distributions were obtained by numerically differentiating integral distributions obtained using the retarding grid analyzer and normalized so as to coincide at $V_{RET}=0.5$ V. (b) Estimate of the energy distribution of epithermals obtained by subtraction of the 5 keV incident energy differentiated spectrum from the 1 keV spectrum.

(Nangia et al, J.Appl.Phys 91,2818(2002)

Cooling between linac pulses

- After 3.3 ms the earliest the SiC should be ready for the next pulse
- If not cooled into the potential well, positrons may annihilate on the SiC (loss)
- The gas (CO_2) must cool fast enough (ms range)
- literature: SF_6, CF_4, CO_2 or CO at 10^{-5}-10^{-4} mbar pressure may have ms cooling time
- Cooling between the linac pulses is feasible

TABLE III Positron cooling in a PM trap using molecular gases at 2.6×10^{-8} mbar: time τ, for direct annihilation; measured cooling time, τ_c; and the energies of the vibrational quanta, ϵ_i. Data from Refs.(Greaves and Surko, 2000, 2001).

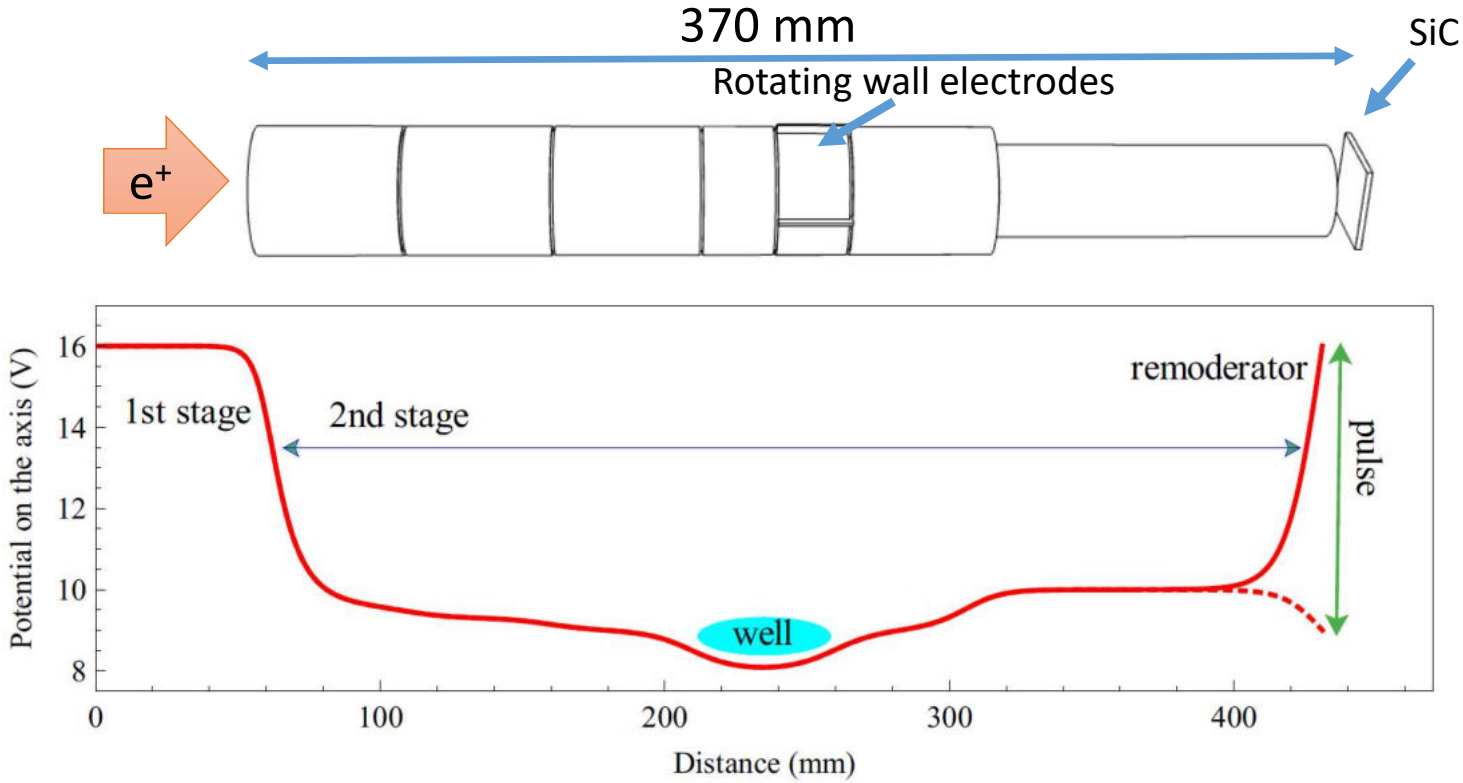
Gas	$\tau_a(s)$	$\tau_c(s)$	$E_\nu(eV)$
SF_6	2200	0.36	0.076, 0.19
CF_4	3500	1.2	0.16
CO_2	3500	1.3	0.29, 0.083
CO	2400	2.1	0.27
N_2	6300	115	0.29

Table from Danielson et al, Rev. Mod. Phys. 87,247 (2015)

Experiment using the second stage of the BGT

- SiC moderator on a moveable sample holder behind the second stage
  + new electrode before the SiC
- The first stage is used to form a potential barrier
- The positrons are cooled into a potential well by CO_2 (or SF_6)buffer gas
- Rotating wall compression to reduce diameter
- Tests performed at 200 Hz (5 ms between pulses)
- Measurement:

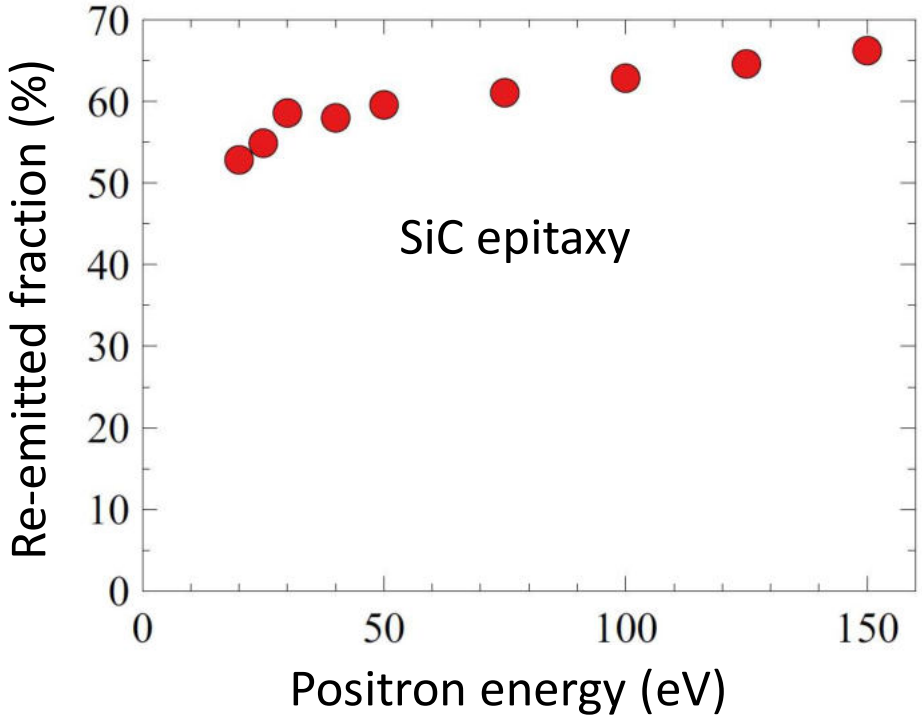
  annihilation signal from trapped positrons ejected on the SiC kept at -100V
  reference: signal from direct annihilation of the original pulse (SiC at -100V)
  detector: CsI scintillator



Verification of the moderator efficiency of SiC

- High quality epitaxial SiC

  4H polytype, n type (N) <$5x10^{15}$ cm^{-3} doping
- Reemitted fraction is measured with linac pulses
- Not a detailed study
- Confirms our earlier results (~60 % efficiency)



Trapping efficiency

- Accumulation for 100 ms (21 pulses)
- Optimization
  - Buncher pulse
  - Gas pressure
  - Potential well
  - Moderator potential
  - Rotating wall frequency and amplitude
- Best result: ~40 % trapping efficiency*

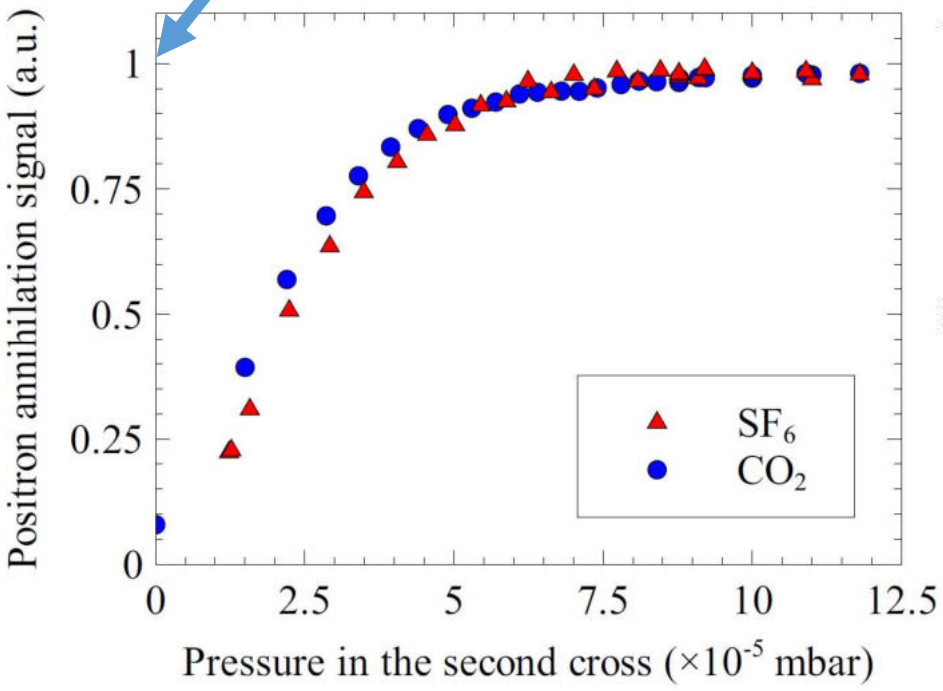
*(defined a trapped positrons as a function of the positrons which reach the SiC remoderator)

Gas cooling

- 5 ms repetition time (200 Hz linac frequency)
- Annihilation in the gas is small in the time scale used (~0.1 s)
- Signal saturates above ~5x10^{-5} mbar

  ➔ cooling is fast enough to confine positrons into the potential well in 5 ms
- No difference between CO_2 and SF_6

~40 % trapping efficiency



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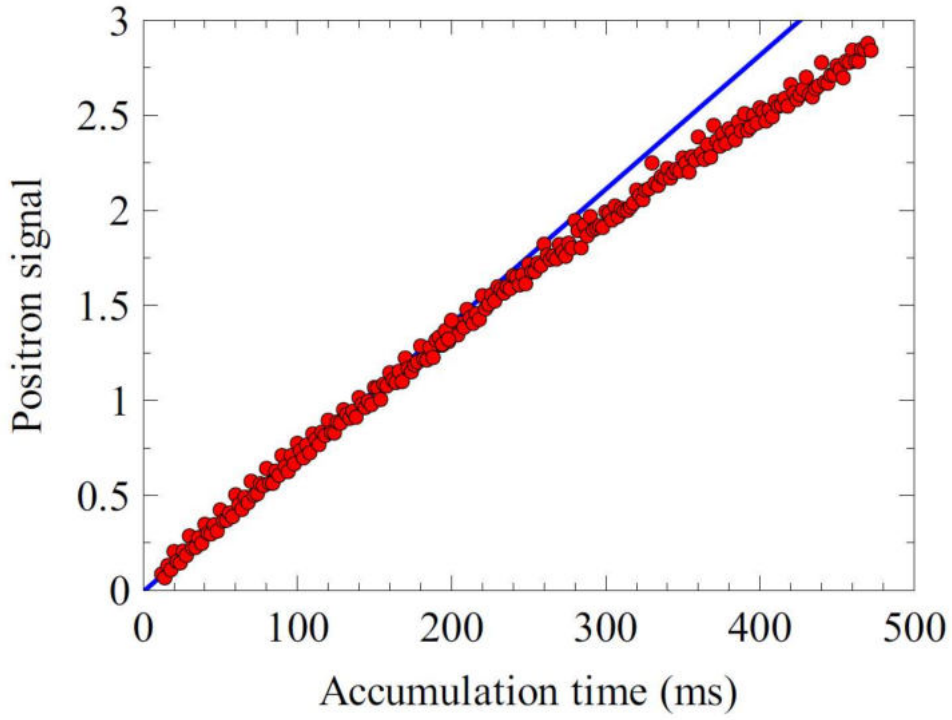
Accumulation of positrons in the potential well

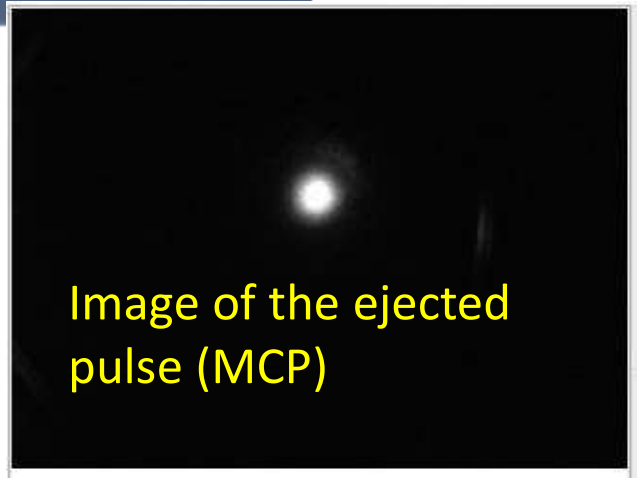
- No significant loss up to ~200 ms, at 300 ms still tolerable

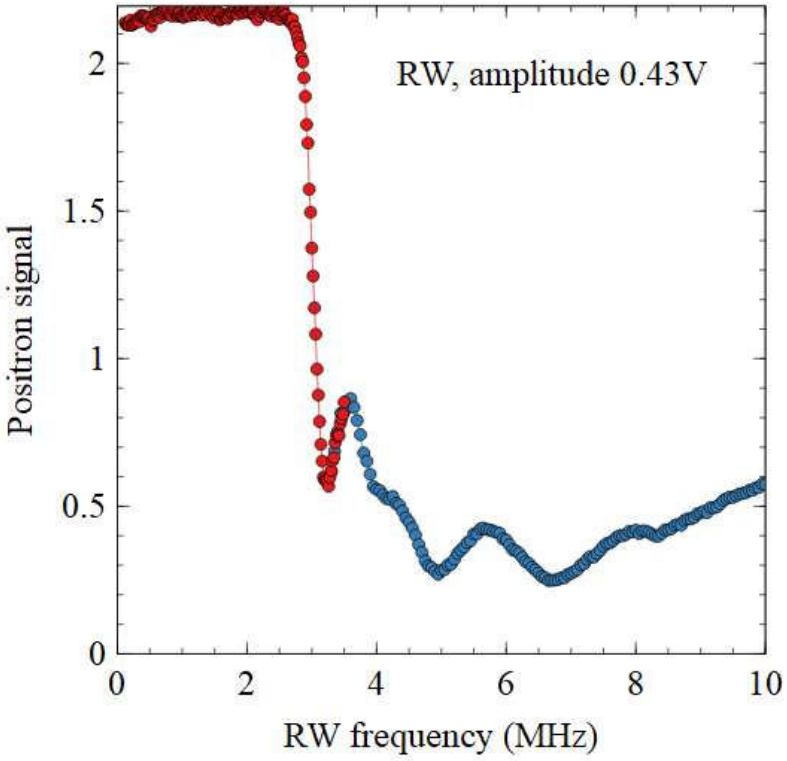


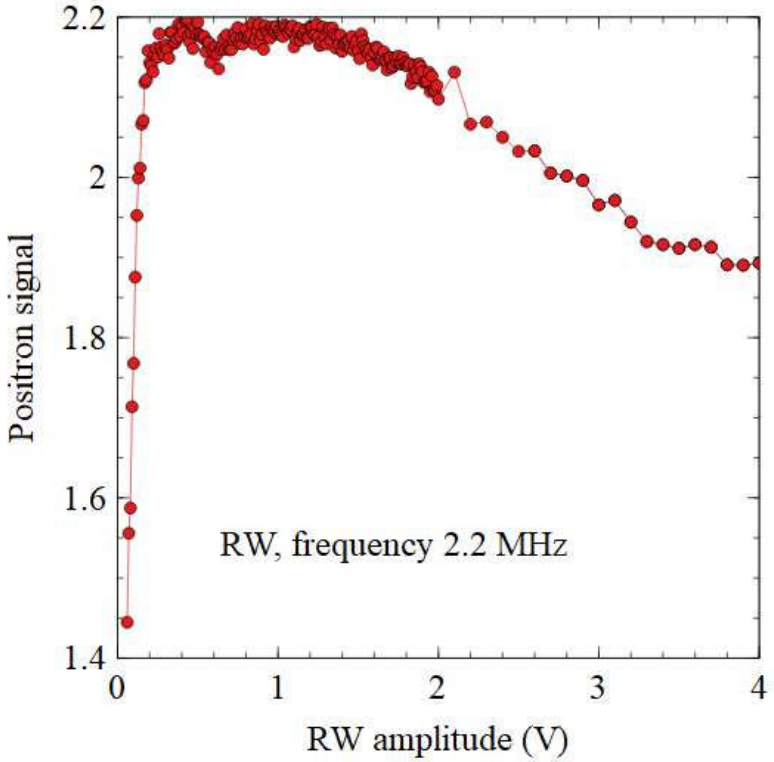
(measurement at 200 Hz linac frequency)

Rotating wall compression

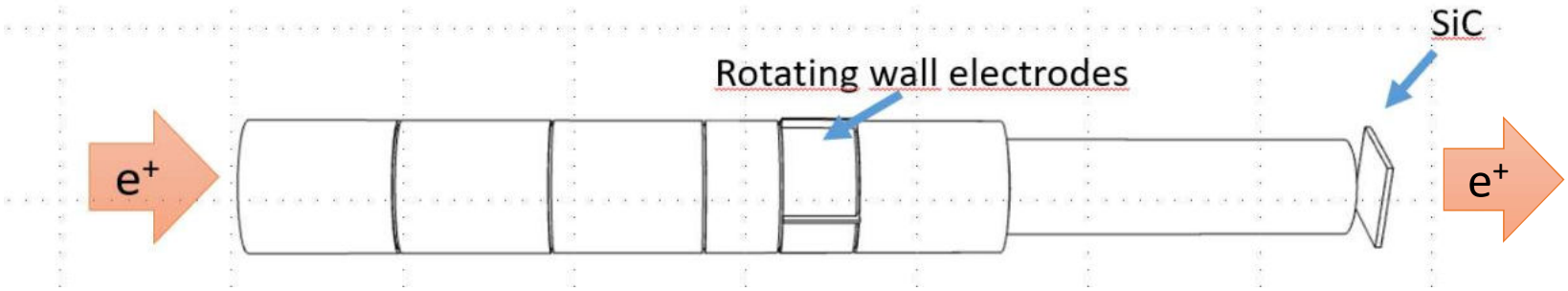
- Rotating wall is on all the time
- Compresses the positron cloud
  to avoid loss
  to reduce size before transfer to 3rd stage
- Essential for high trapping efficiency
- Result: small diameter, good compression







Transport from the trap



- The SiC remoderator is in the way when the positrons are ejected from the trap
- Several methods are in study to solve the problem:
  - Removal of the moderator (if possible, in 3.3 ms)

    certainly feasible, the speed is a problem
  - Manipulation of the plasma position to pass on the side of the SiC

    feasible but requires changes in the vacuum system
- At the moment, a mechanical movement is being developed (magnetically coupled rotary drive)

Summary and outlook

- Possible alternative to trap positrons from a linac-based source
- The SiC based scheme works, with an efficiency of ~40 % for 100 ms accumulation time
  - About three times higher as the actual efficiency with the conventional BGT
  - Higher than the efficiency reported for ^{22}Na – based systems
- Only small loss up to 300 ms accumulation time
- 3rd stage is needed for longer accumulation

- The present configuration is not optimized for the SiC scheme
  - The remoderator is in a divergent magnetic field (vacuum cross)
  - The bunching pulse is not yet perfectly optimized
  - The trap could be longer to accomodate better the pulse
- With an optimized setup, better efficiency may be possible, up to ~60 %

The GBAR collaboration

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THANK YOU