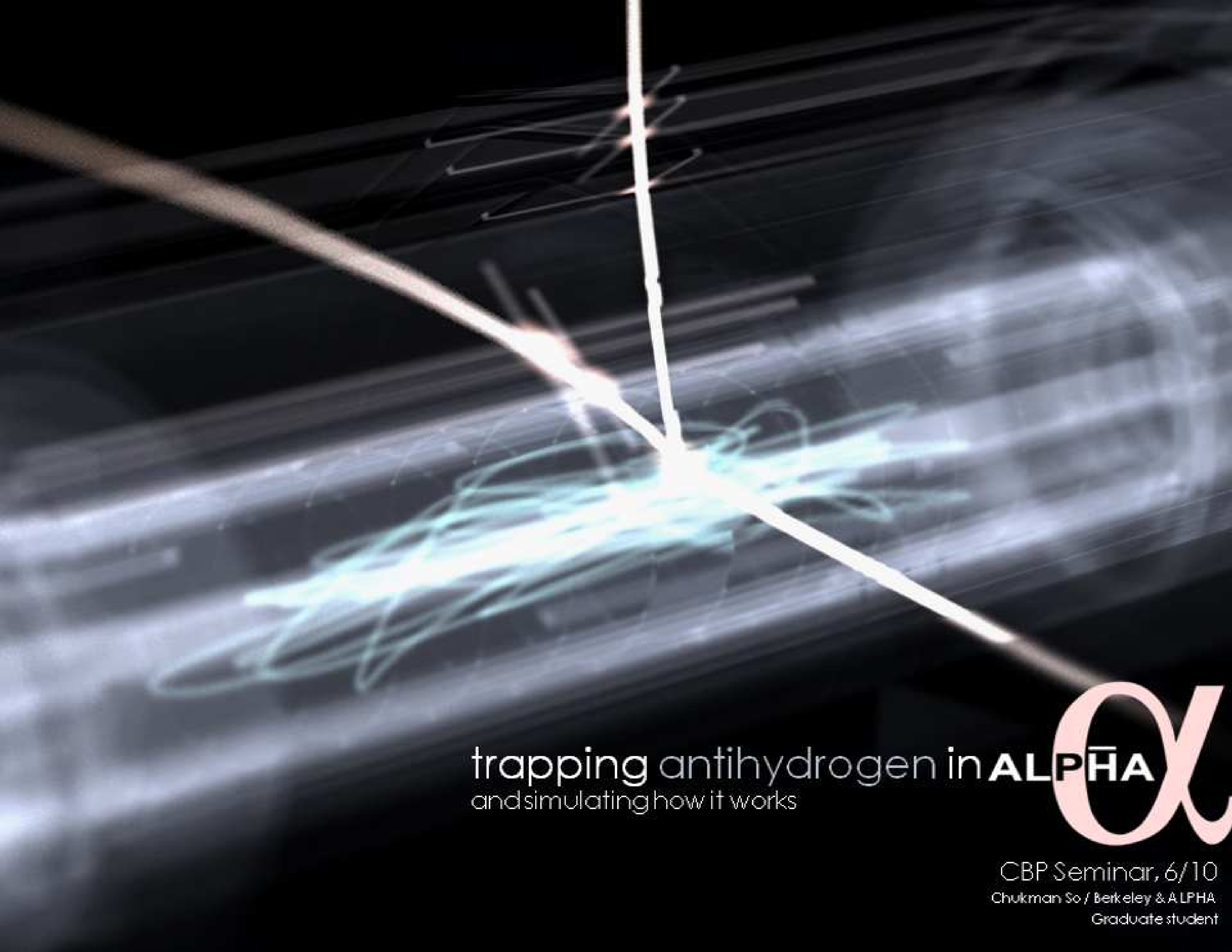


trapping antihydrogen in ALP$\bar{H}$A

and simulating how it works

CBP Seminar, 6/10

Chukman So / Berkeley & ALPHA
Graduate student

why antimatter atom?

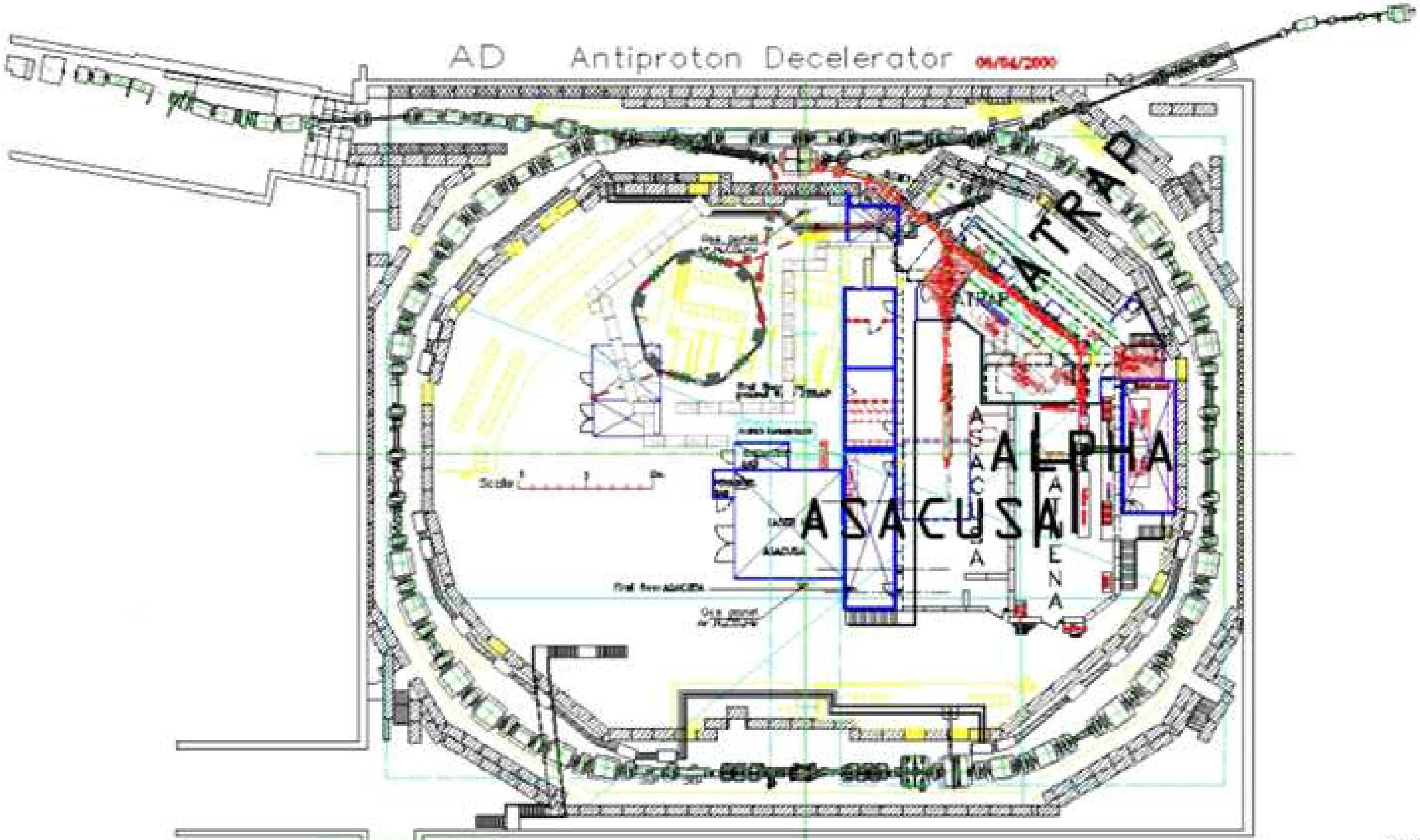
- It's cool
- Matter-over-antimatter preference in Big bang
- CPT symmetry
  - Is hydrogen atom symmetric under CPT transformation?
  - Hydrogen: best understood
    1S – 2S transition: 1 in 10^{14}
    Ground state hyperfine splitting: 1 in 10^{12}
  - Verify CPT in new sector
  - No theoretical assumption
- Gravity
  - How does antimatter fall on an Earth made of matter?
  - Neutral atom: no electric influence

what does it take?

- antiprotons (pbar) – CERN's Antiproton Decelerator
- positrons – Surko-type positron accumulator
- tailoring mechanism
  - Magnets
  - Electrodes
  - Fast sequencer
  - Quiet amps
  - Rotating walls
- diagnostics
  - Faraday cup, multichannel plate, temperature spill, Si strip detector, scintillation detector, NaI detector, modes measurement, etc etc
  - simulation
- holding – nested Penning-Malmberg trap
- mixing – autoresonance injection
- trapping – magnetic minimum trap
- detecting – Si vertex reconstruction

the Antiproton Decelerator

- CERN 2000
- Provides low energy antiproton pulses for experiments
  - 12 M pbar in 500 ns pulses every 105 s
  - 24 h operation for 6 – 7 months a years



Walter Oelert / CERN

the Positron Accumulator

- Design pioneered by the Surko group at UC San Diego
- Provides bunches of slow positrons
  - Continuous ^{22}Na source
  - Buffer-gas cooled
  - Cycle time: ~150 s
  - 300 K (25 meV), 2E+07 positrons

solenoid

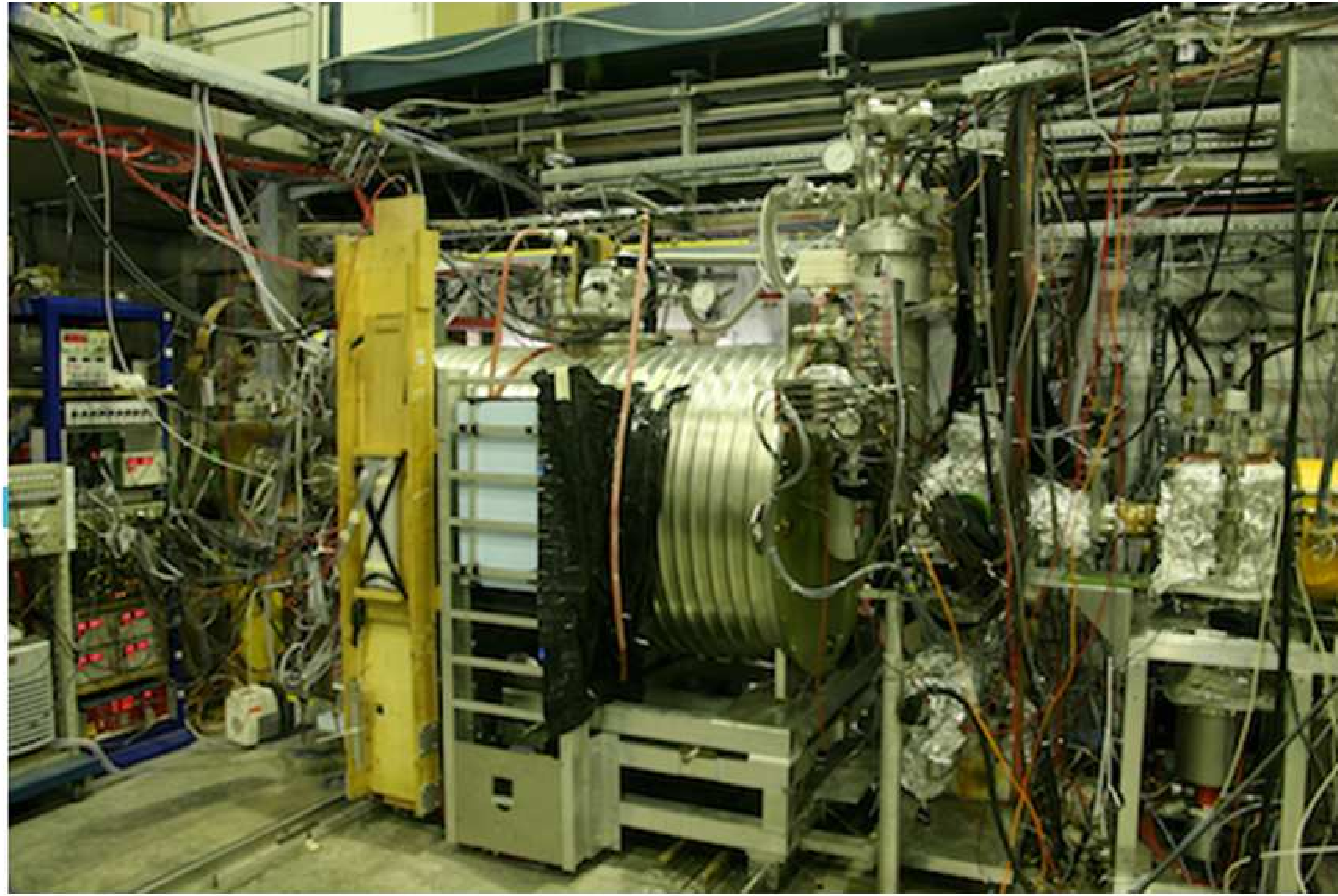
Niels Madsen/ CERN

Positron Accumulator in ALPHA

Niels Madsen/ CERN

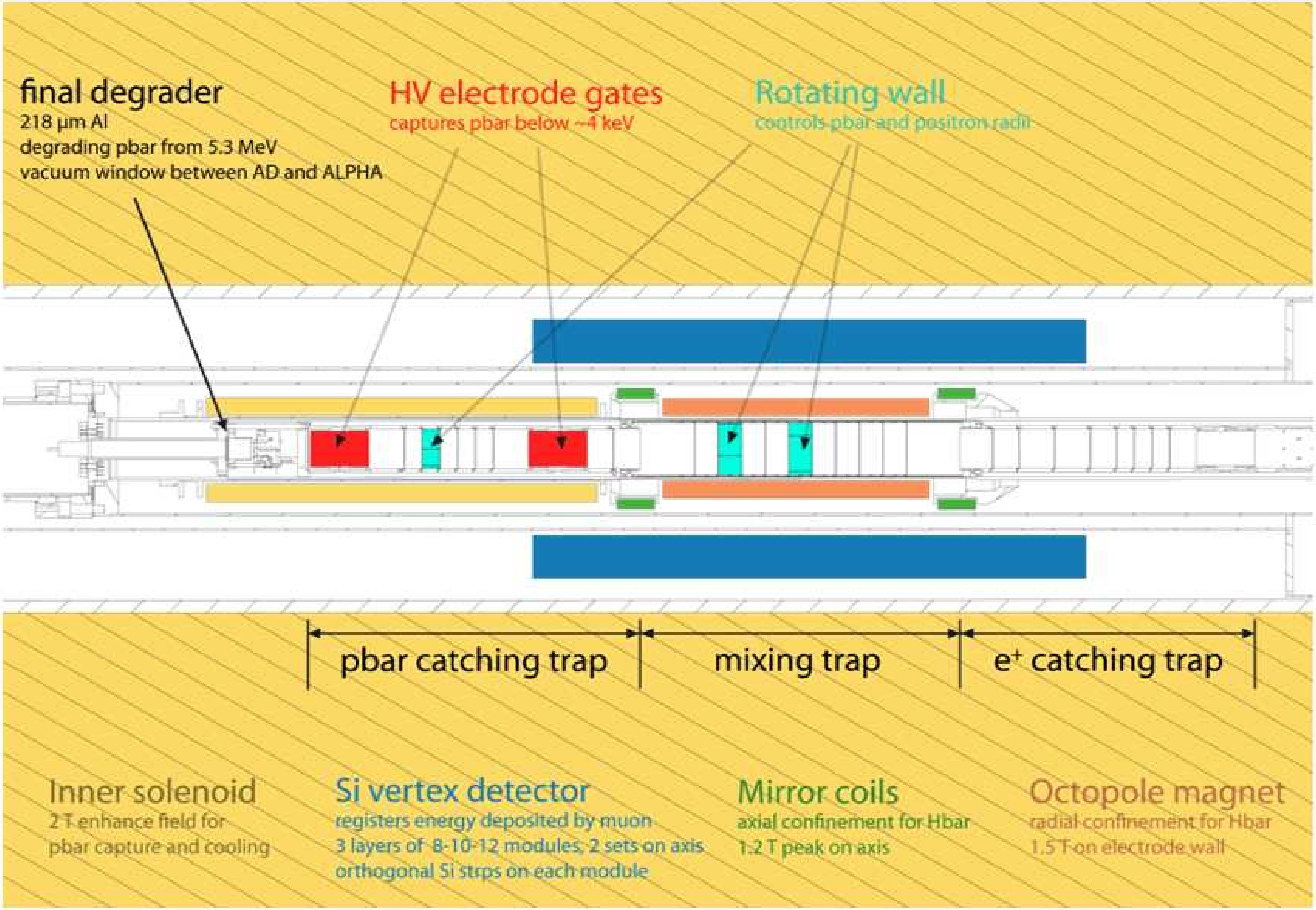
the ALPHA apparatus

AD
$\bar{p}$

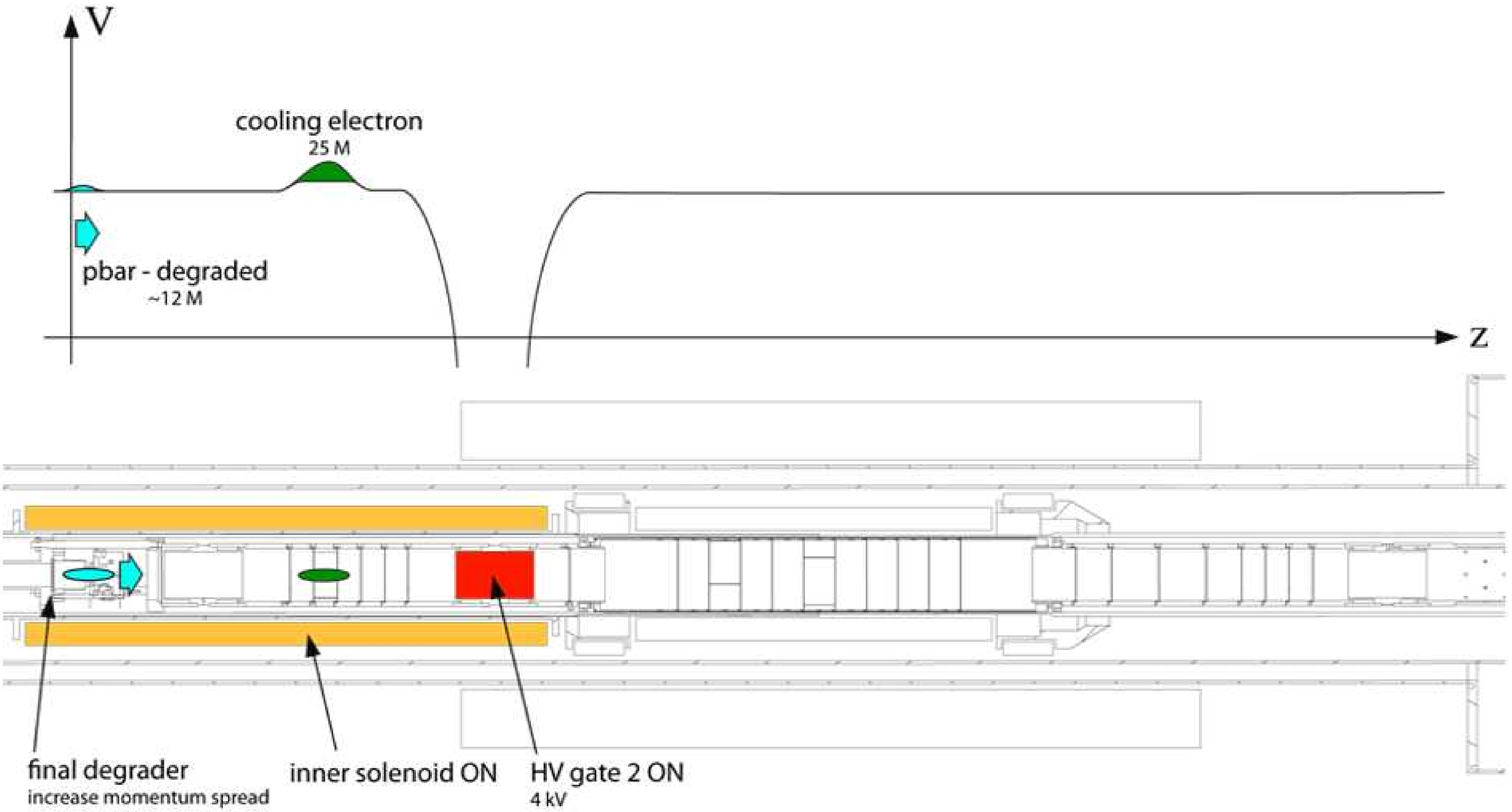


line

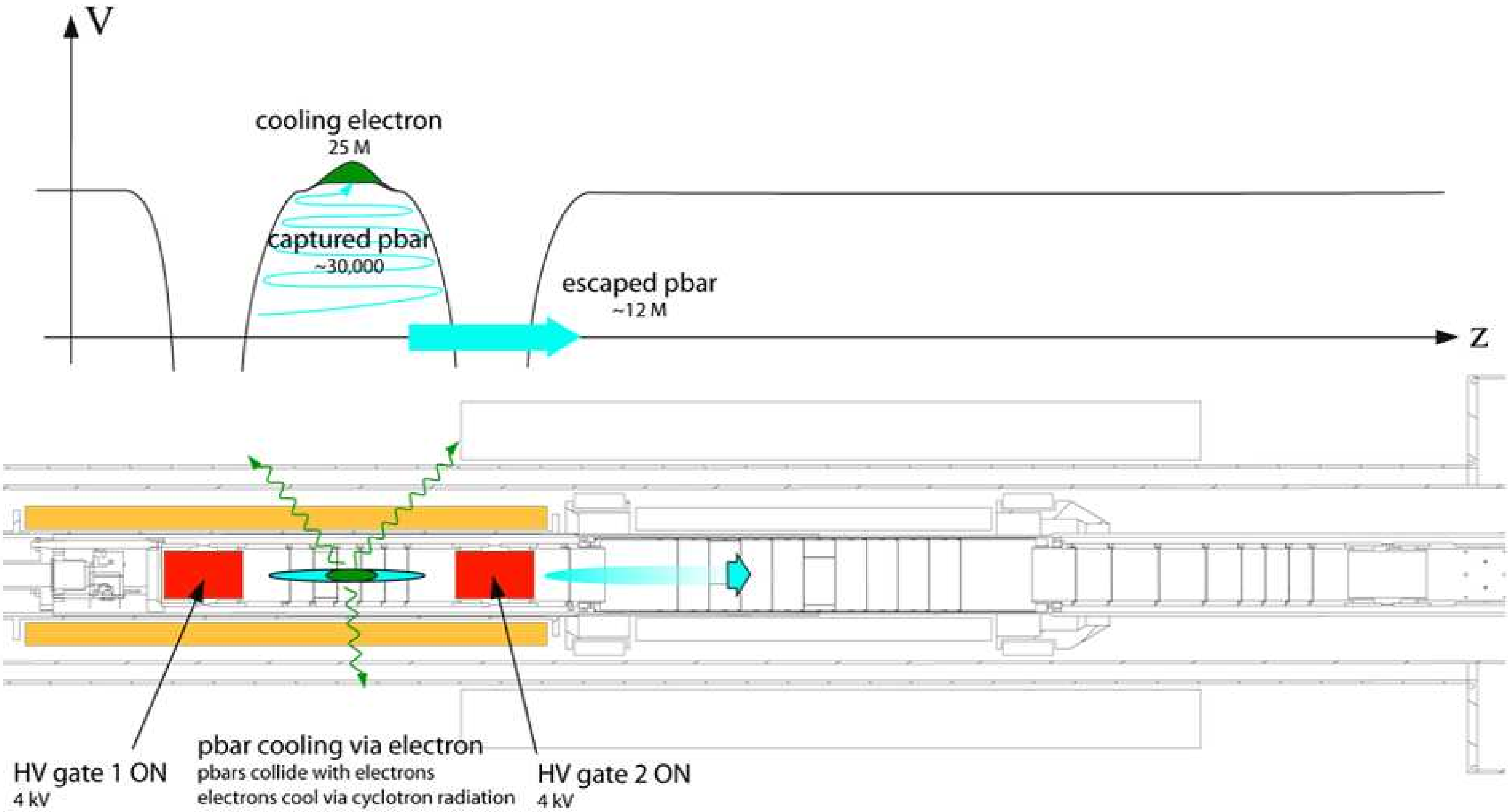
the ALPHA apparatus



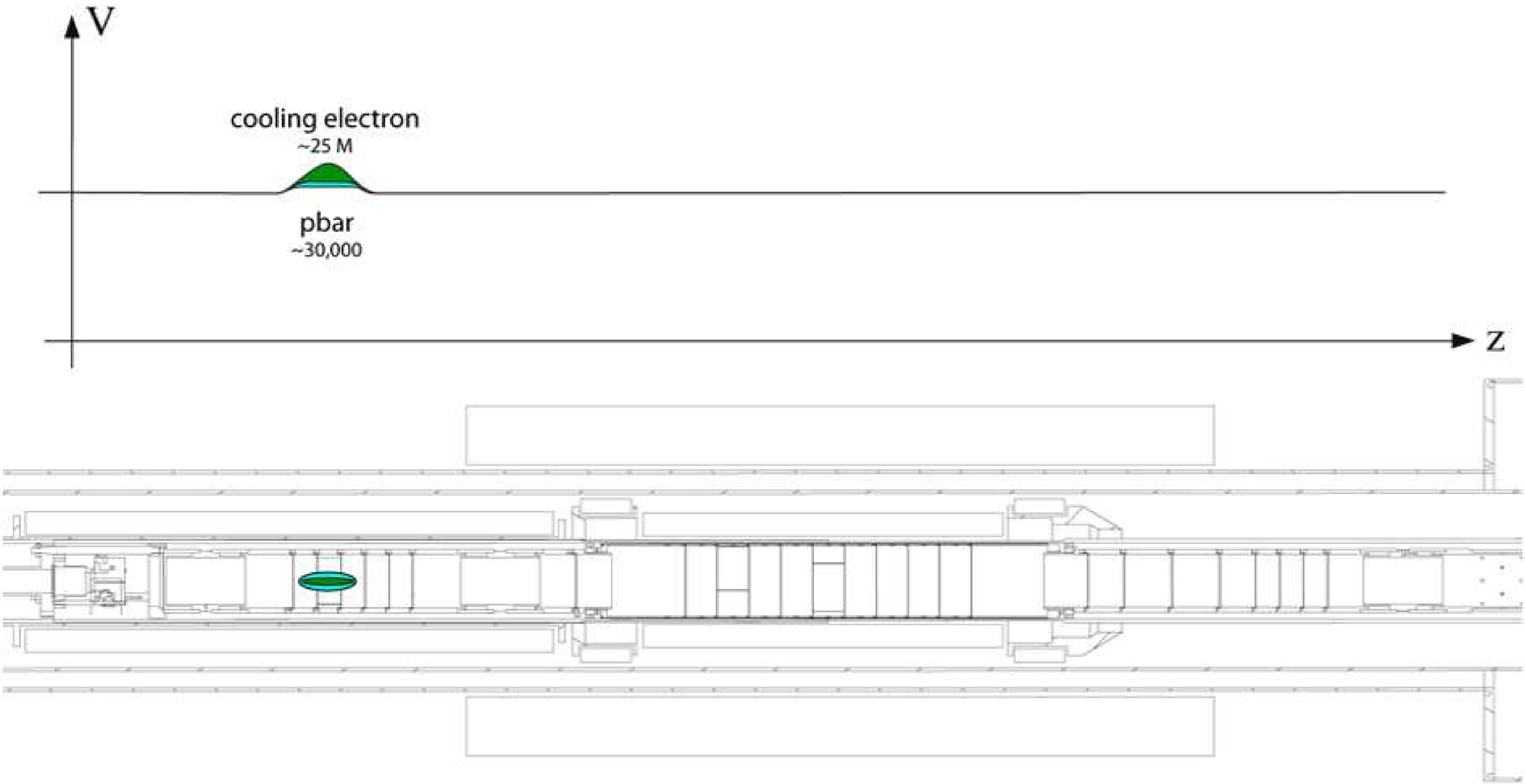
making antihydrogen



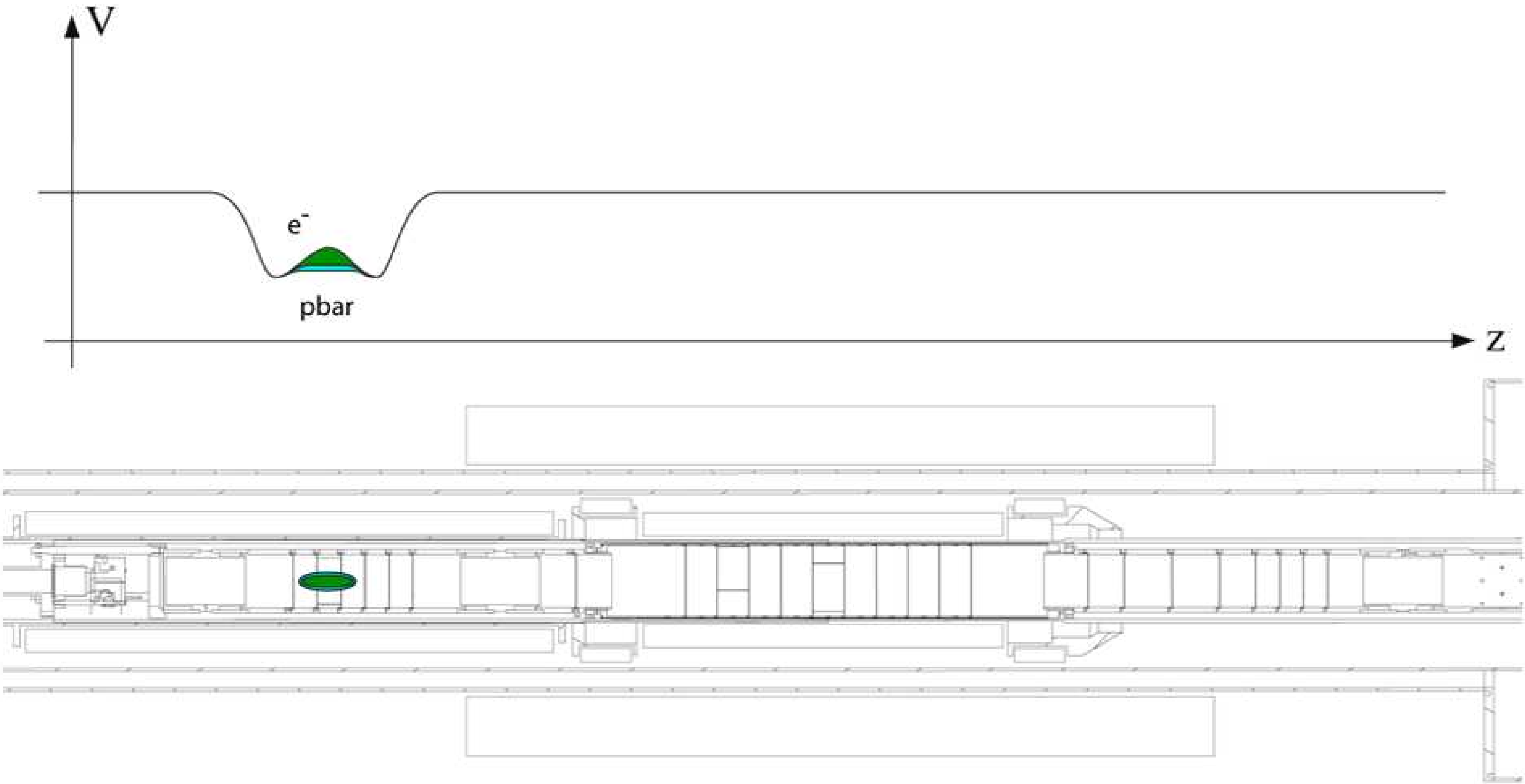
making antihydrogen



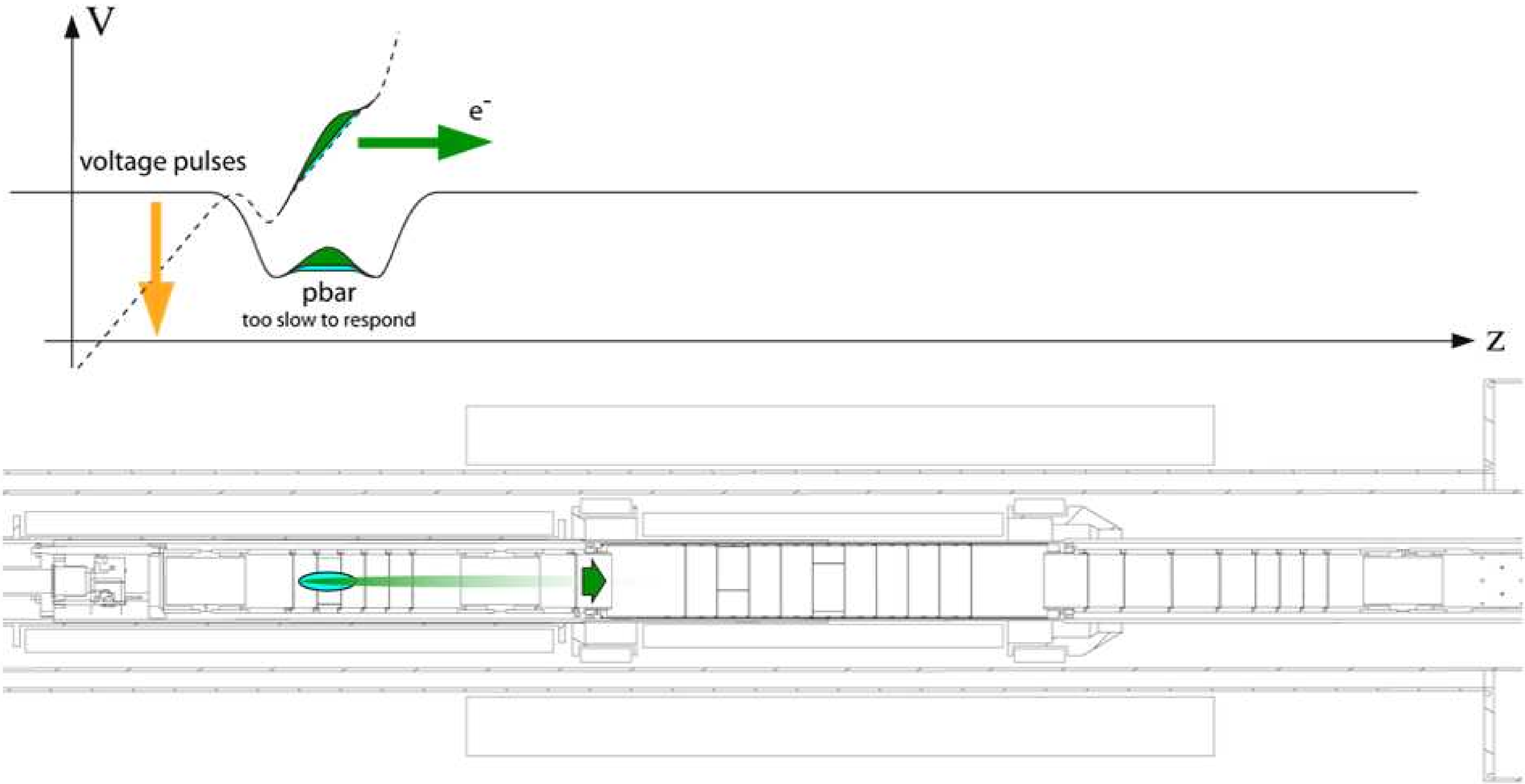
making antihydrogen



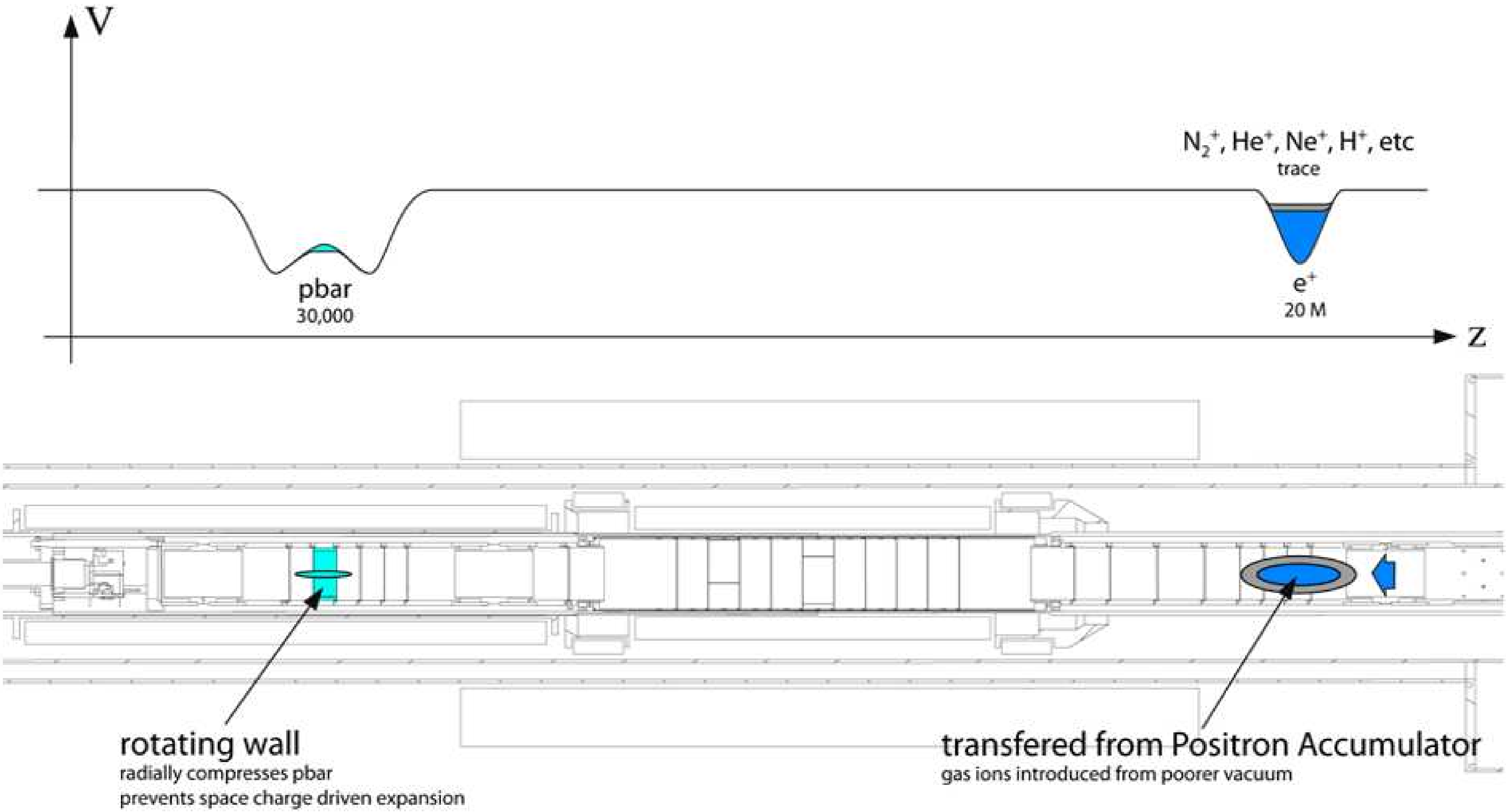
making antihydrogen



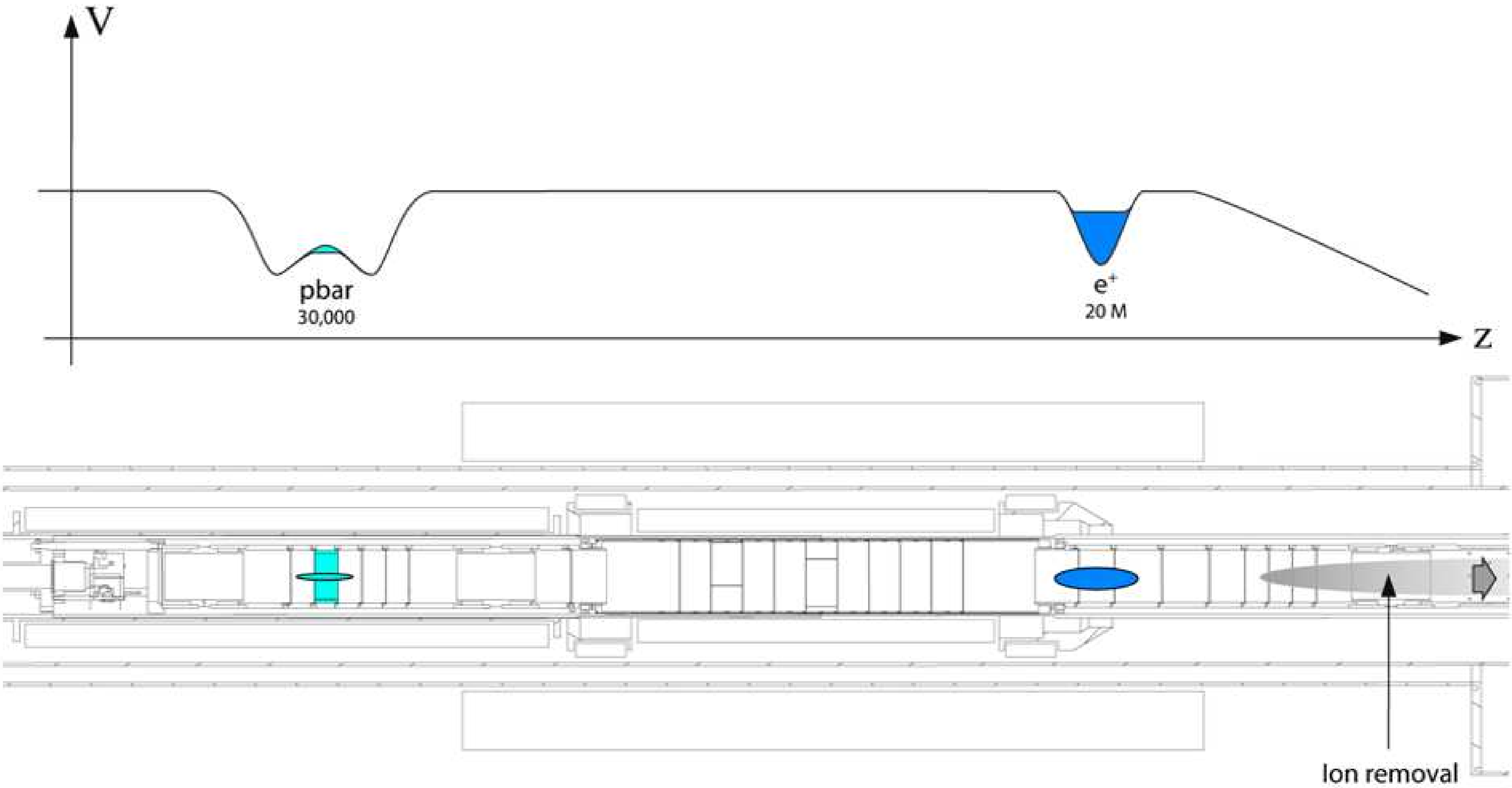
making antihydrogen



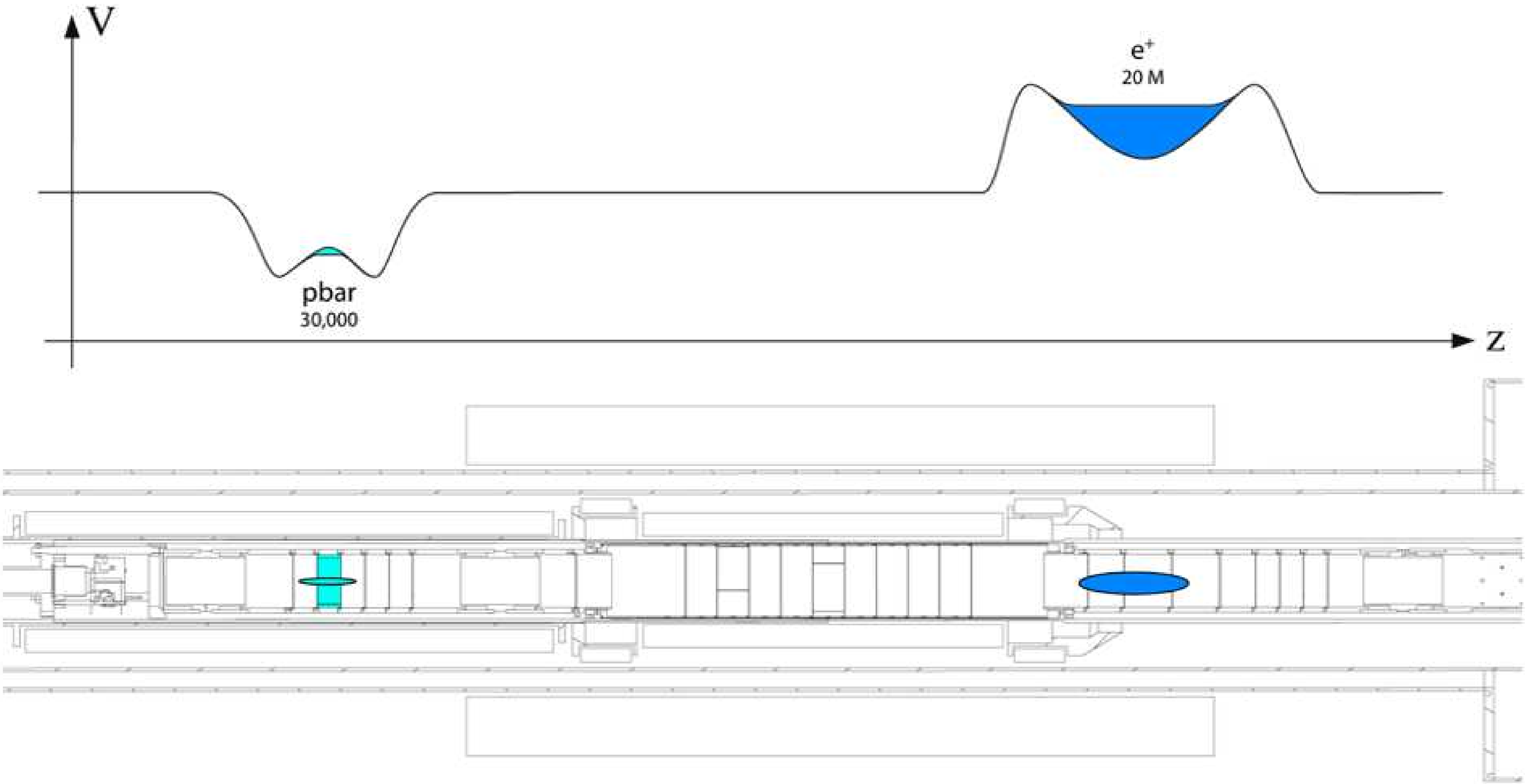
making antihydrogen



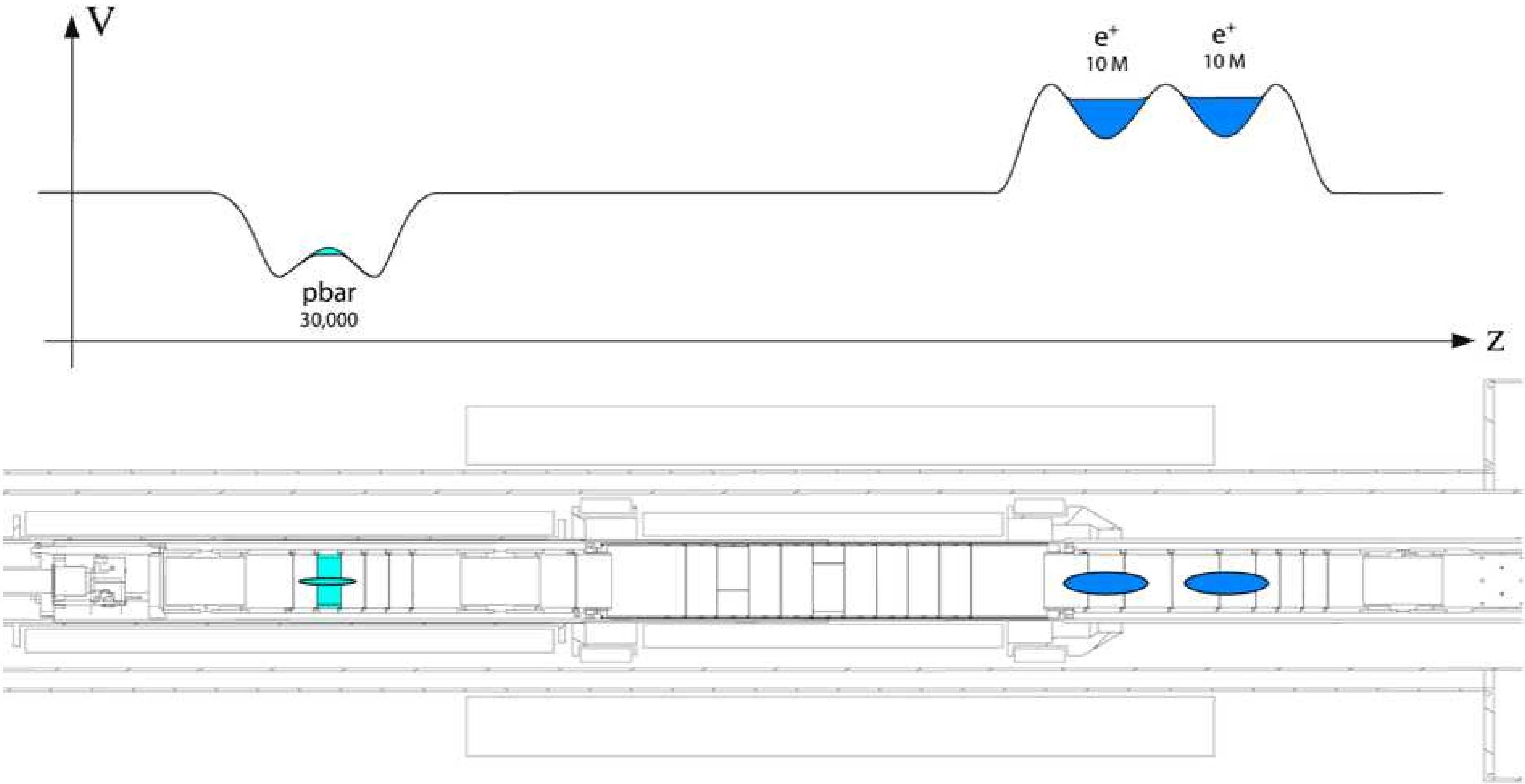
making antihydrogen



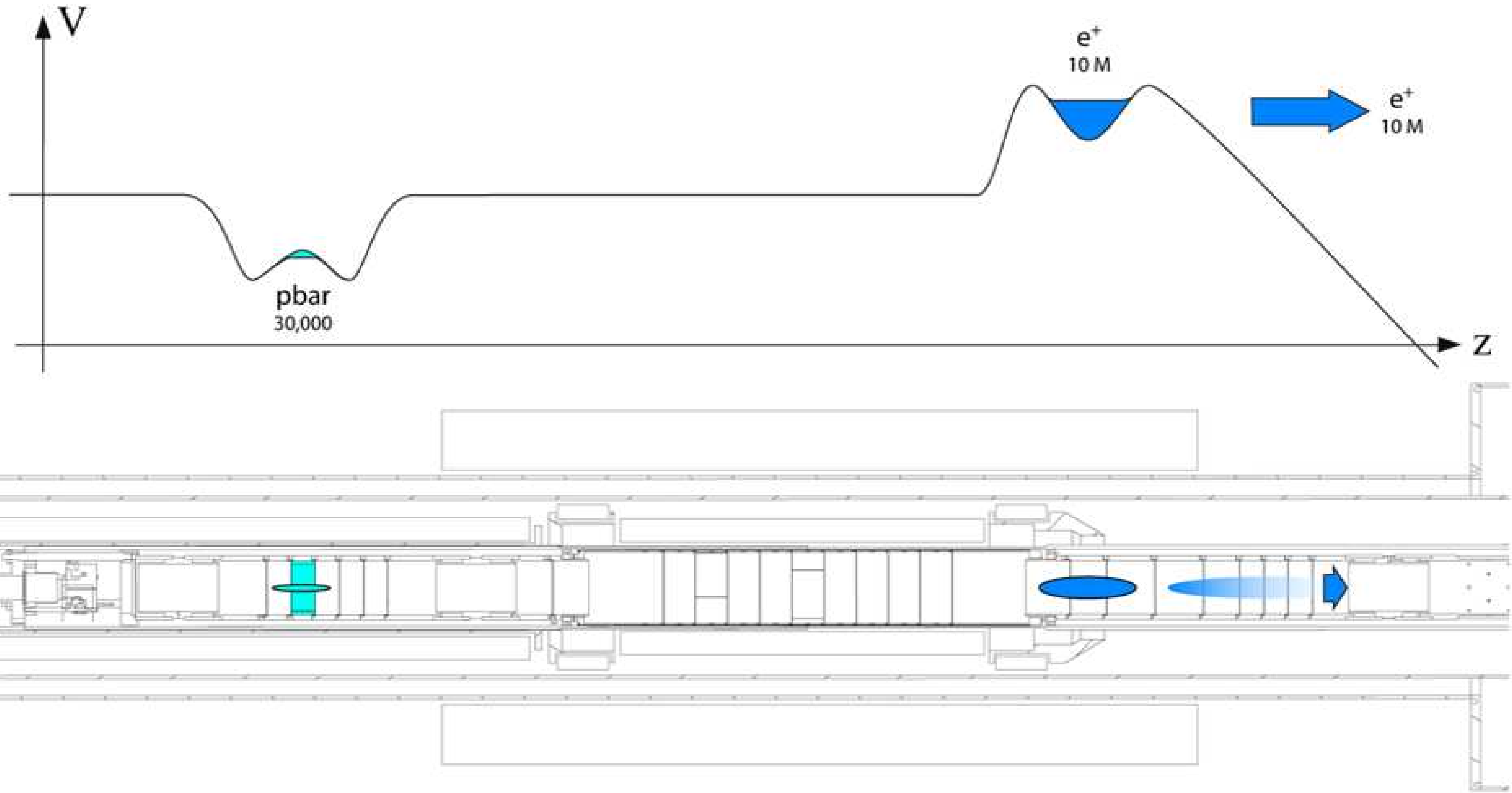
making antihydrogen



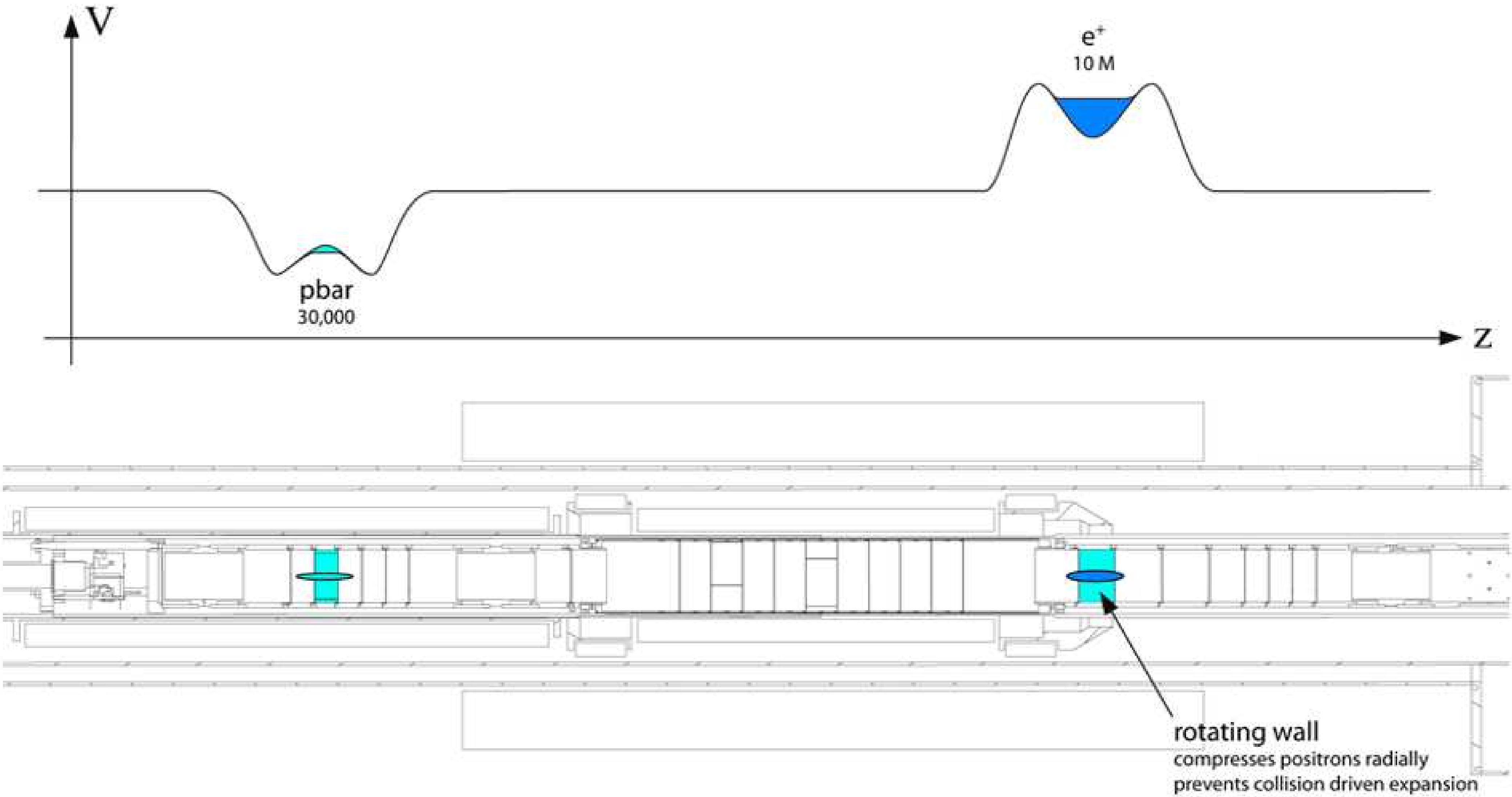
making antihydrogen



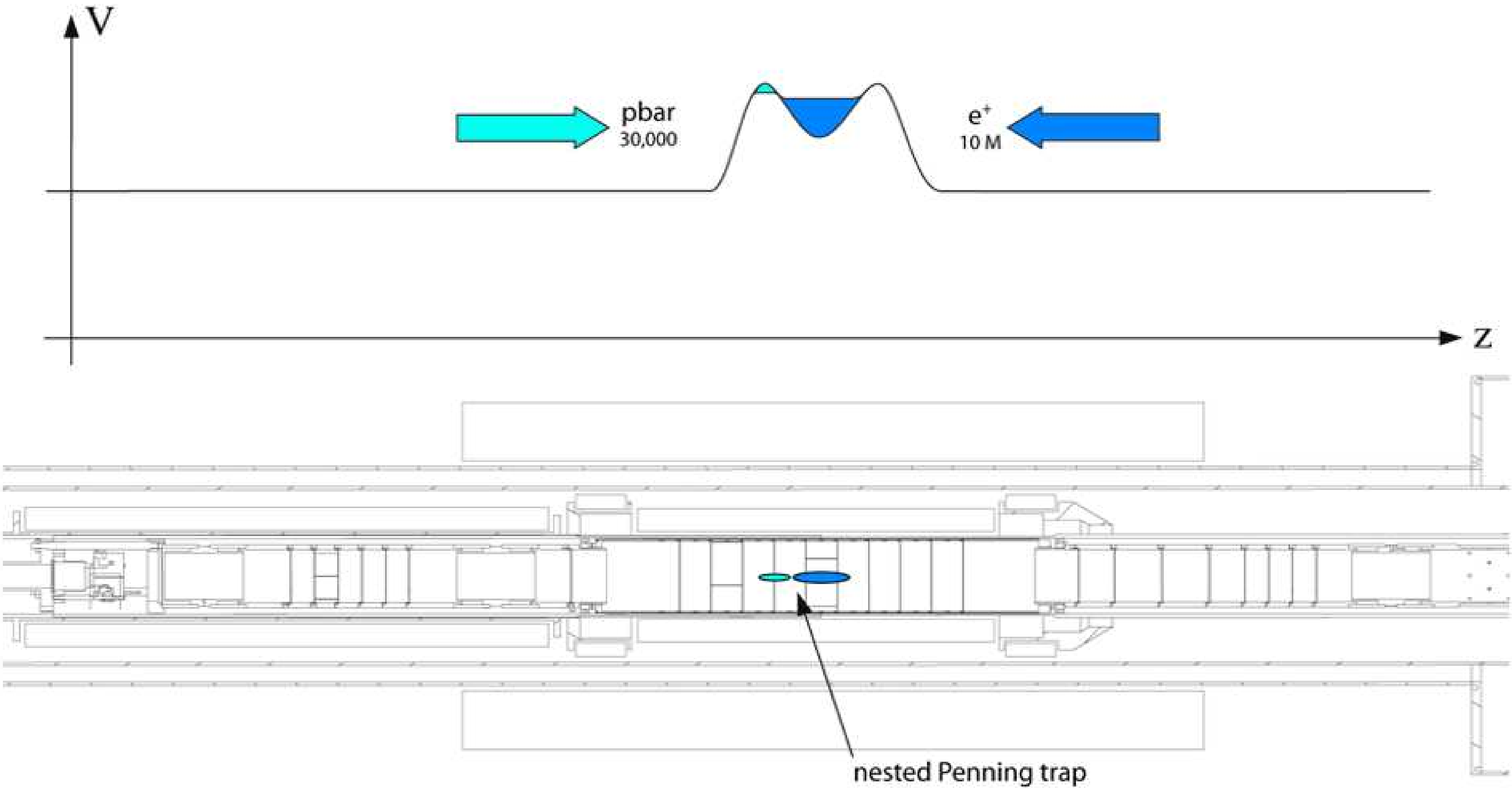
making antihydrogen



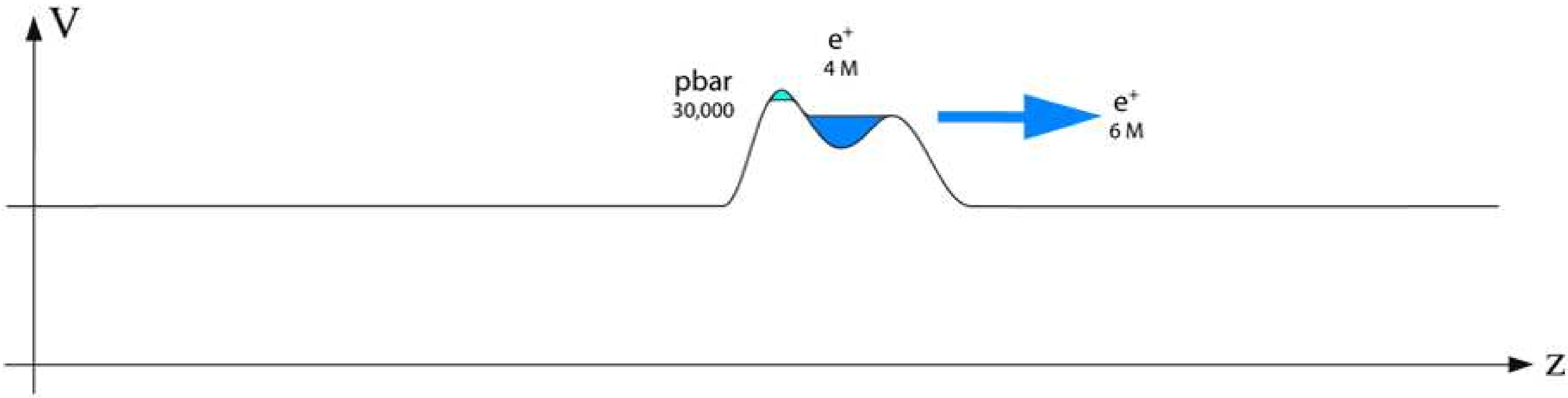
making antihydrogen

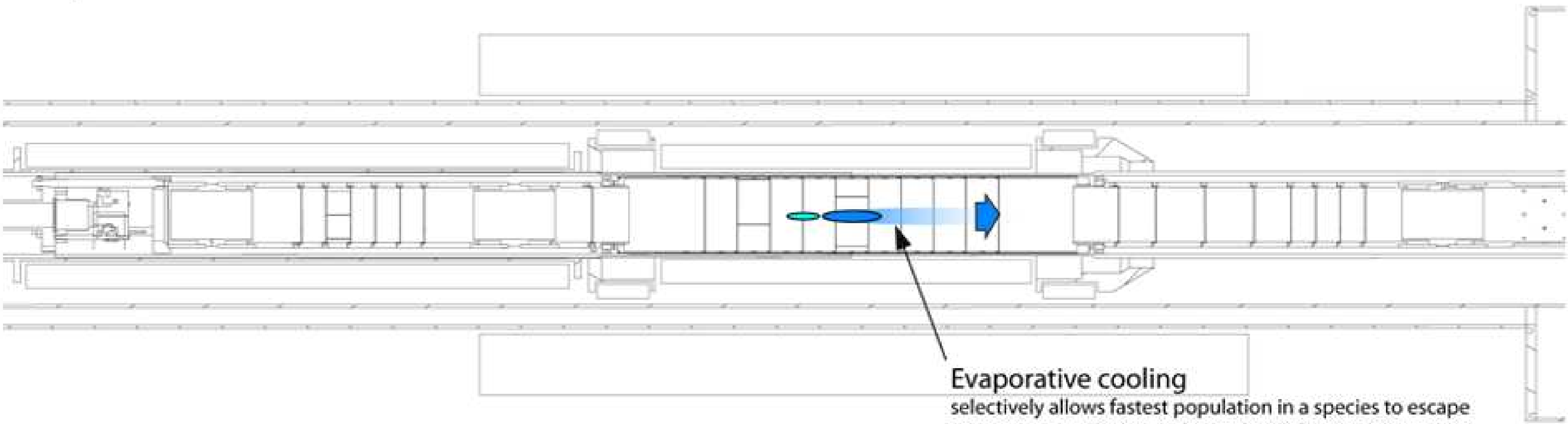


making antihydrogen



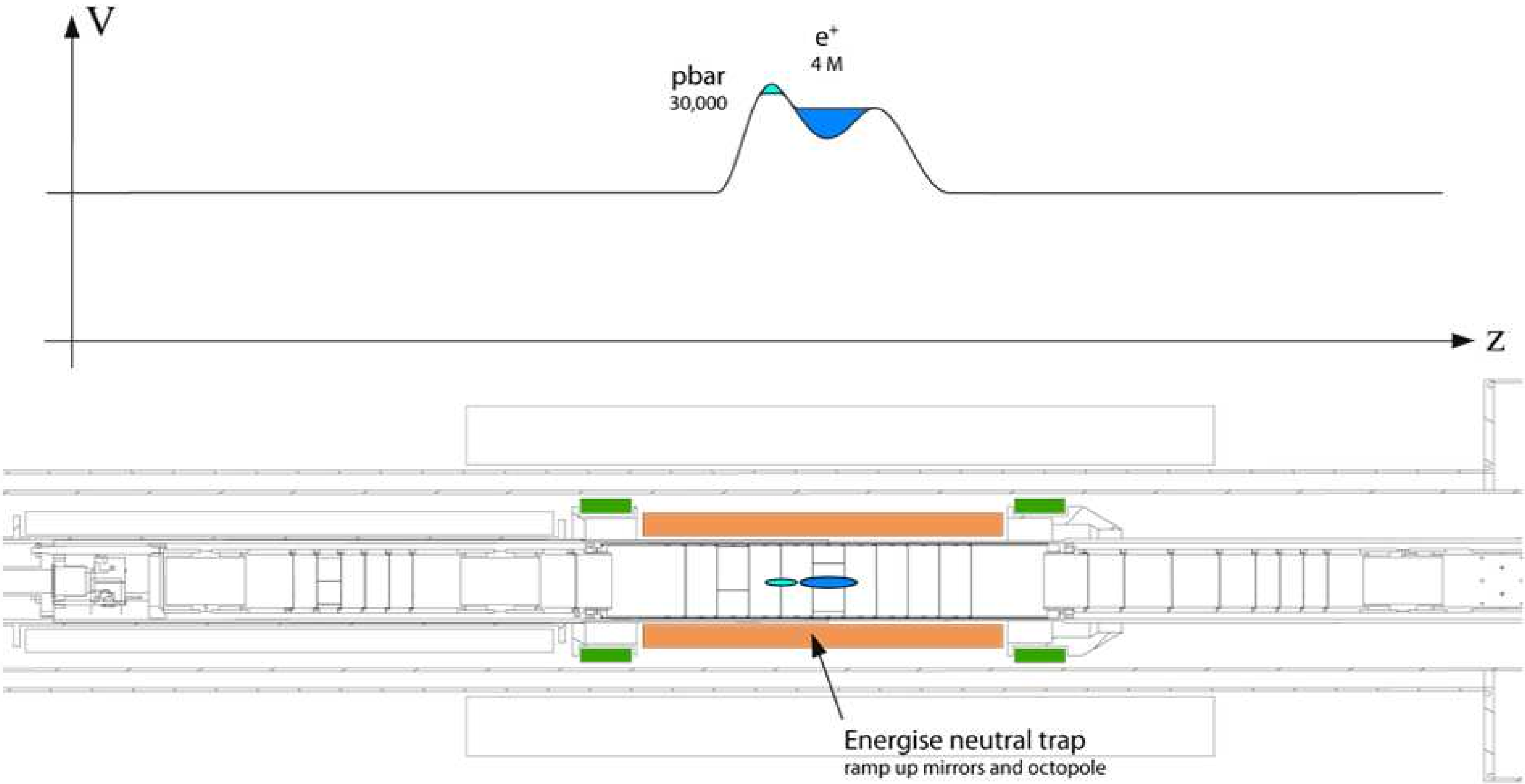
making antihydrogen



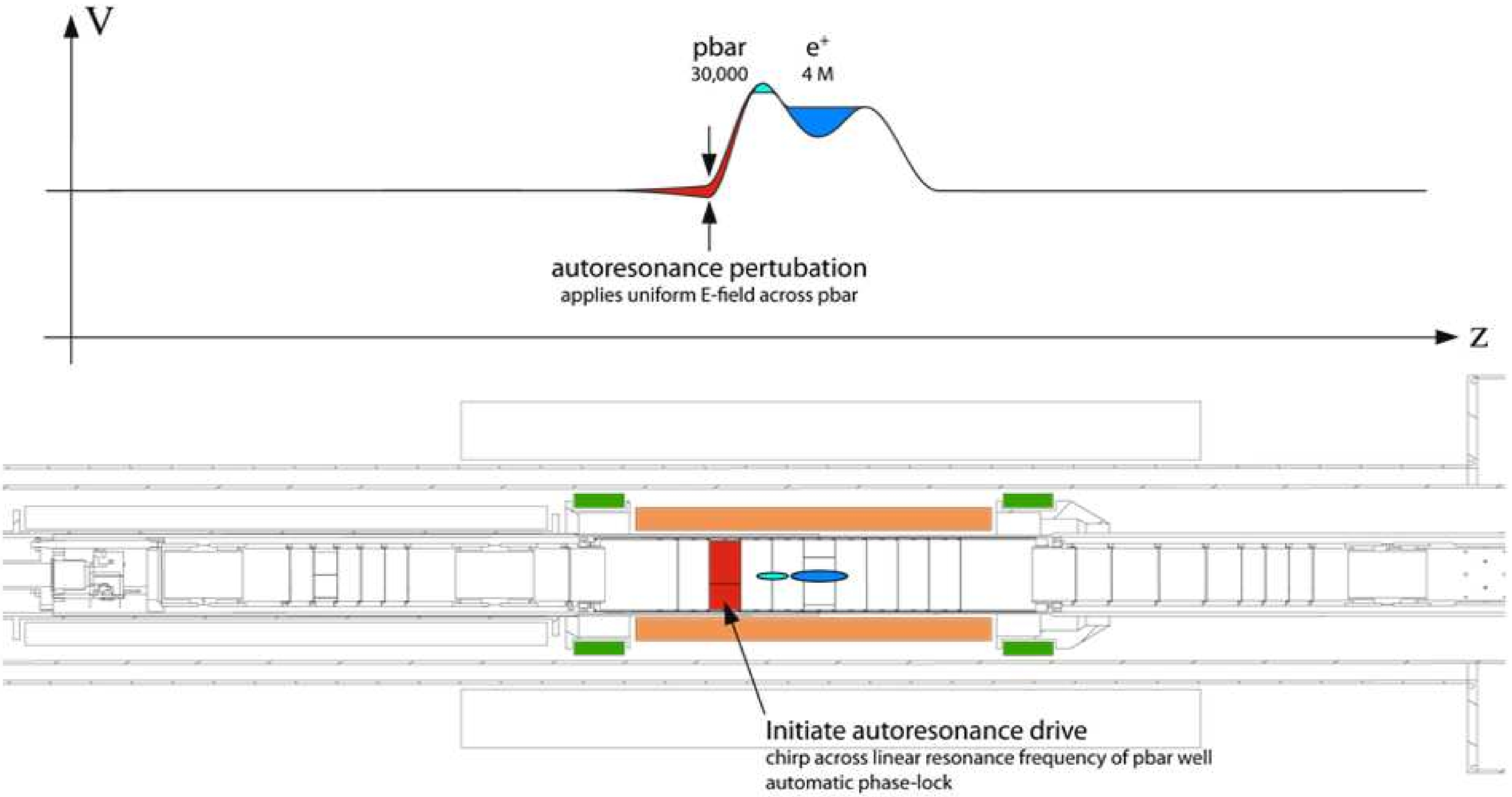


Evaporative cooling
selectively allows fastest population in a species to escape
remaining population re-thermalise to lower temperature

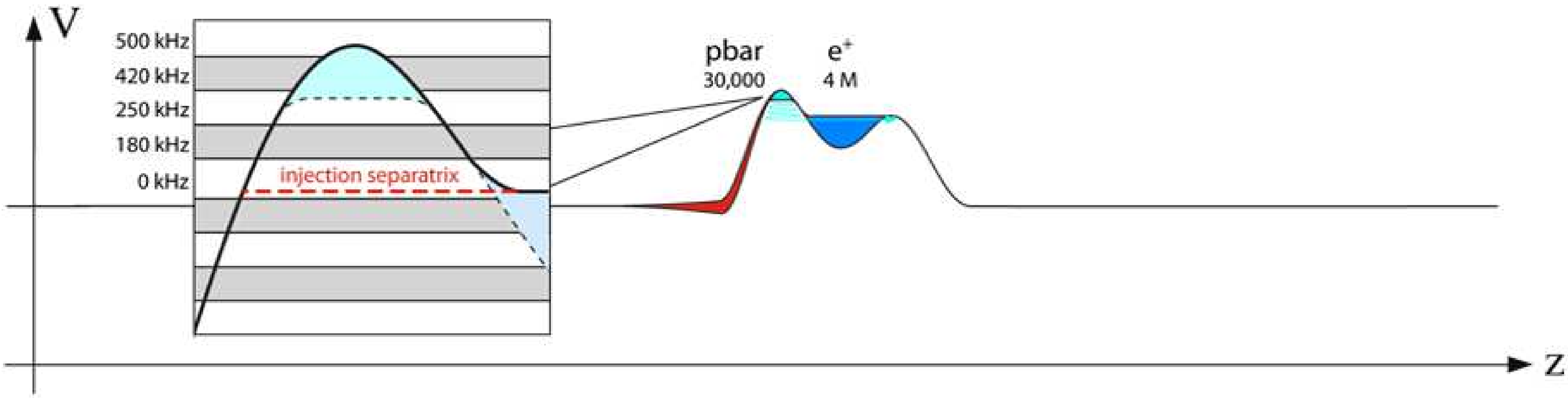
making antihydrogen

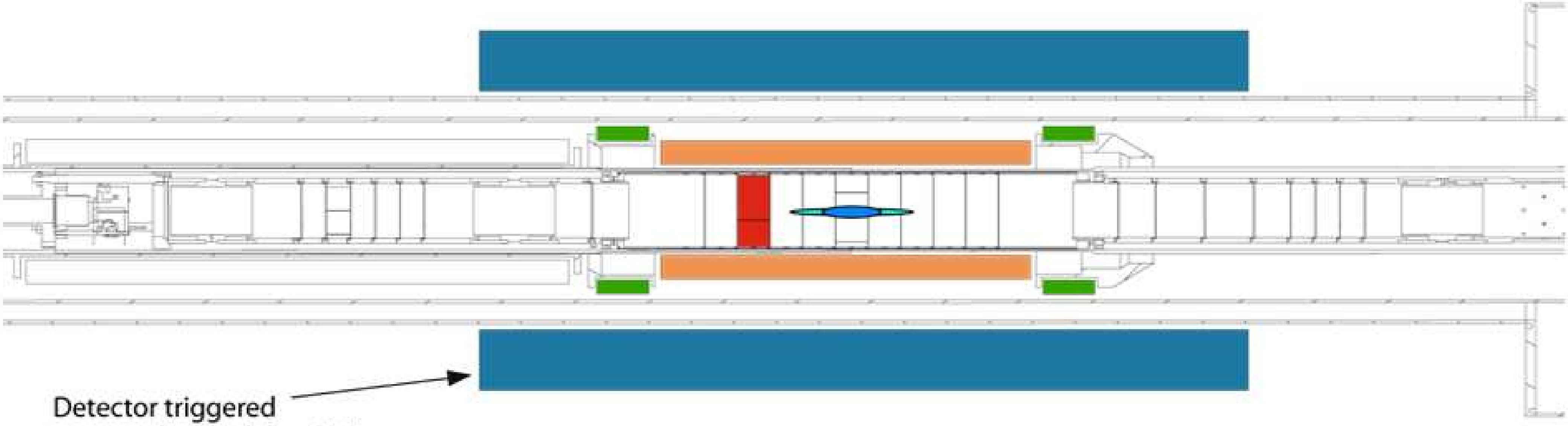


making antihydrogen



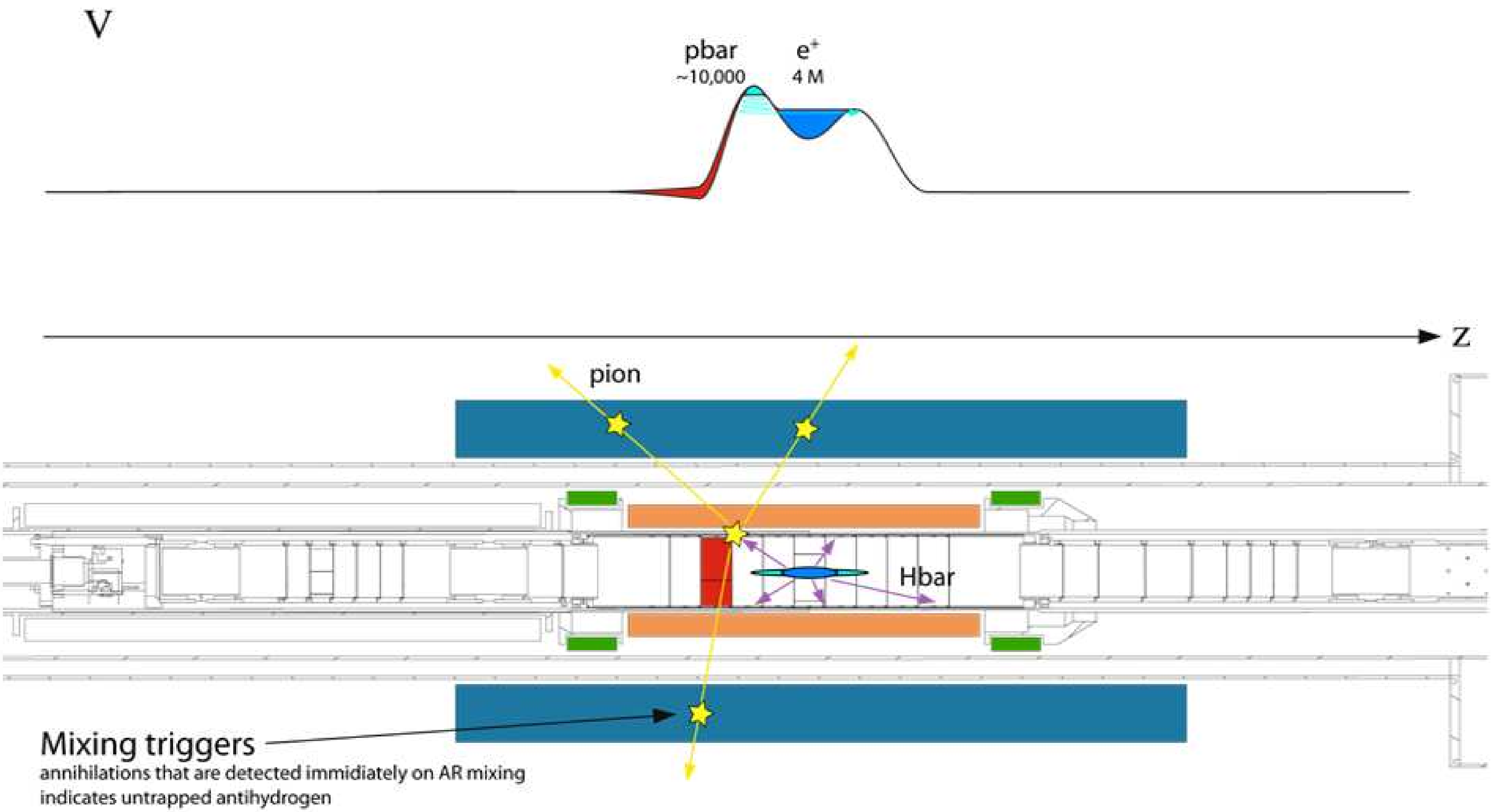
making antihydrogen



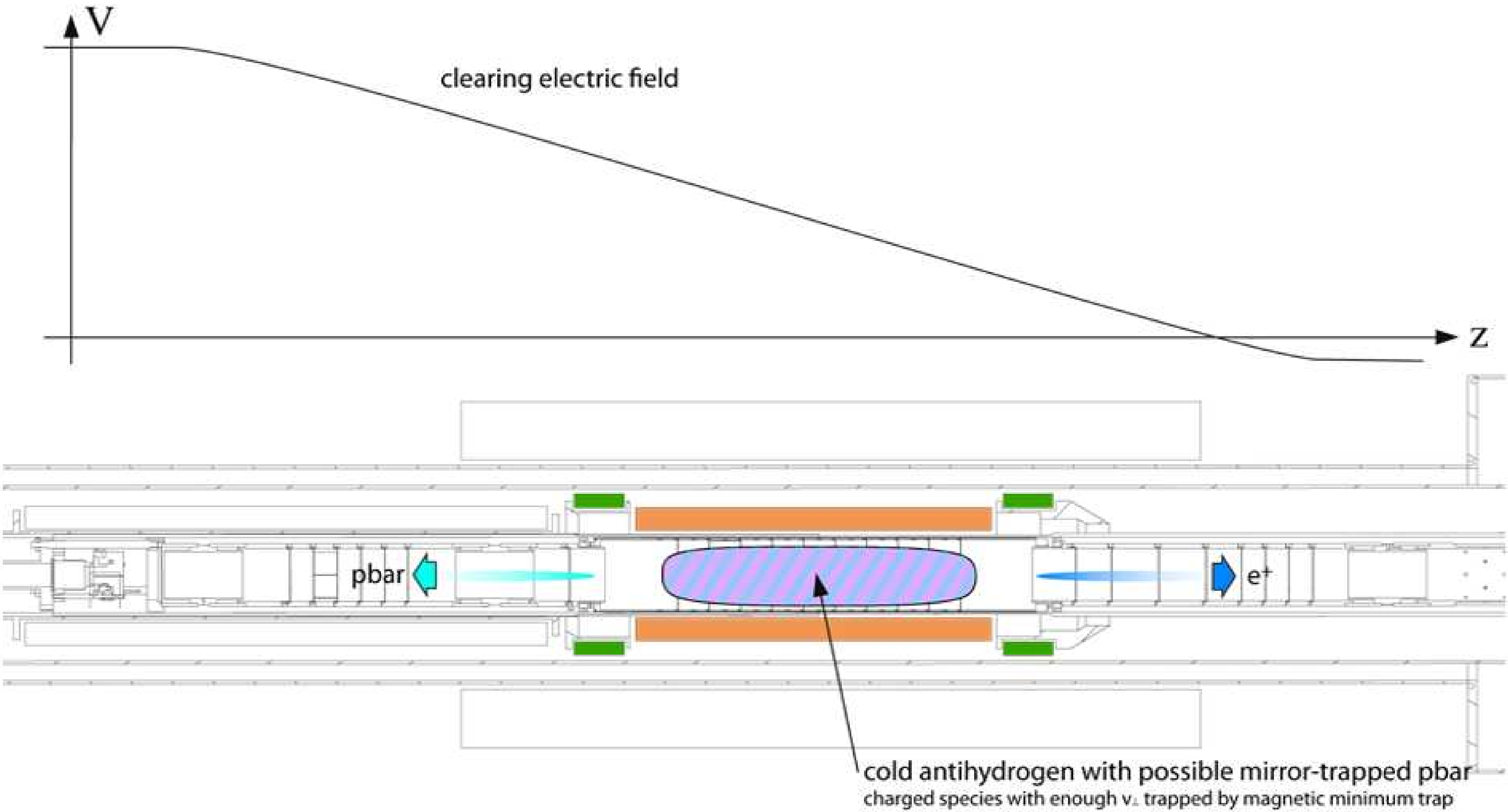


Detector triggered
starts recording signals from Si strips

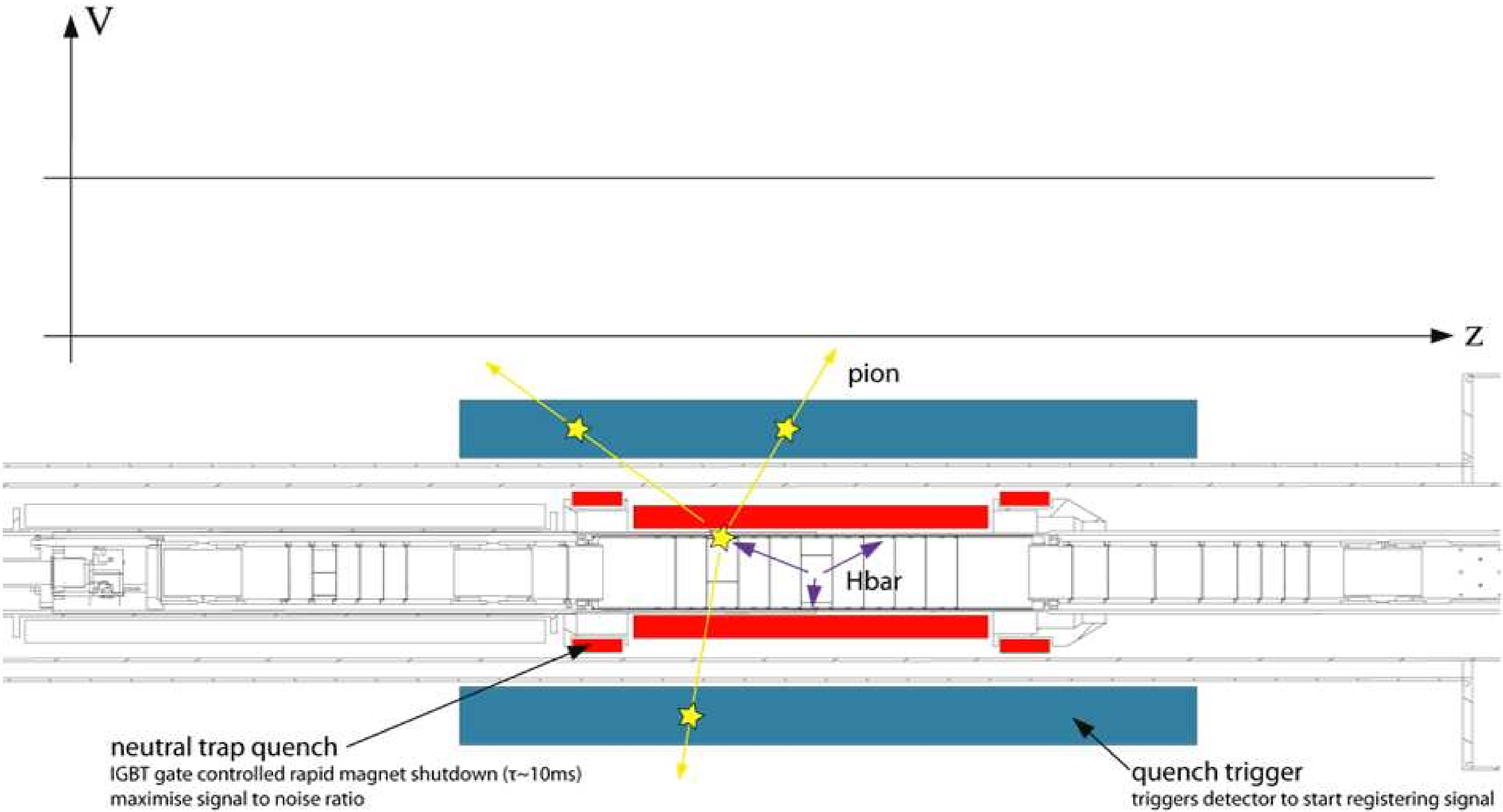
making antihydrogen



making antihydrogen

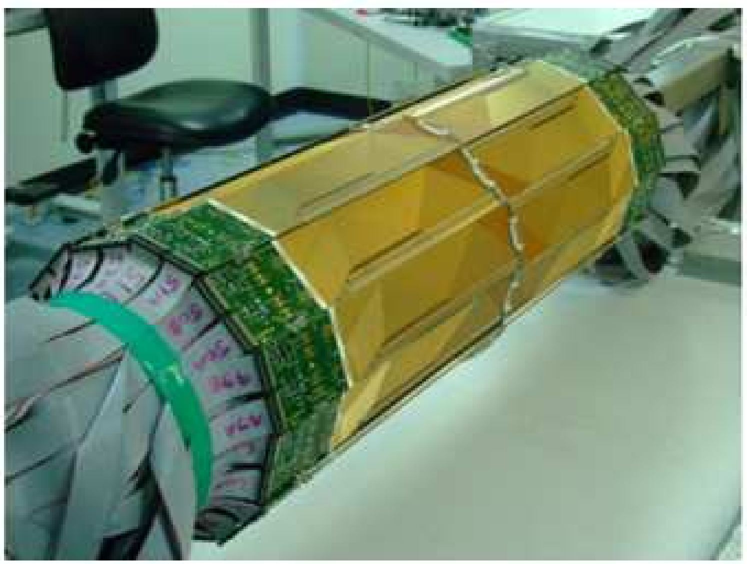


making antihydrogen

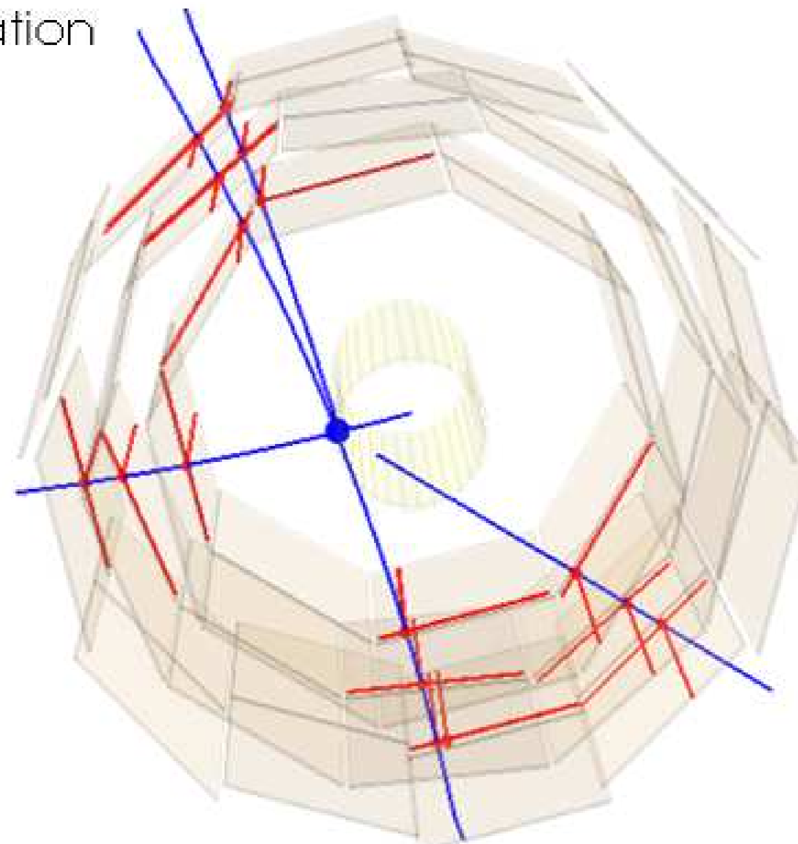


improving signal-to-noise ratio

- Si vertex detector
  - 3 layers
  - Records energy deposition
- Vertex reconstruction
  - Helical track fits through 3 points
  - Min. 2 tracks to retrace point of annihilation



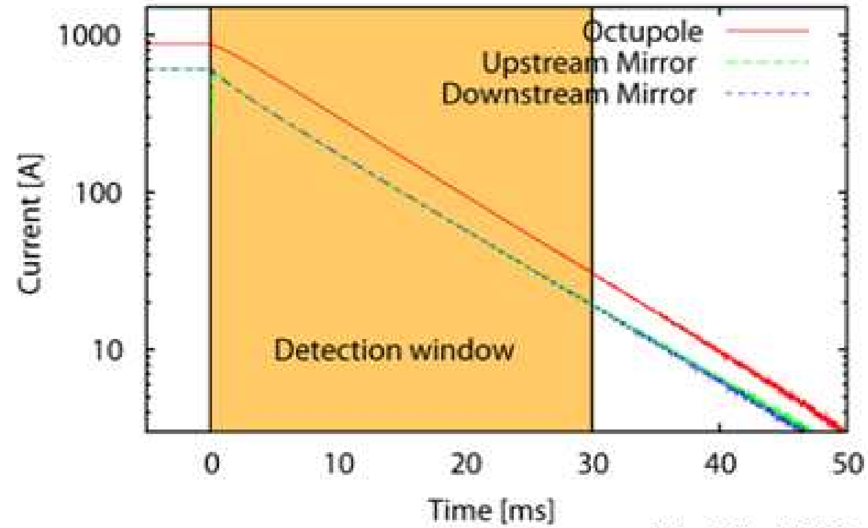
Niels Madsen/ CERN



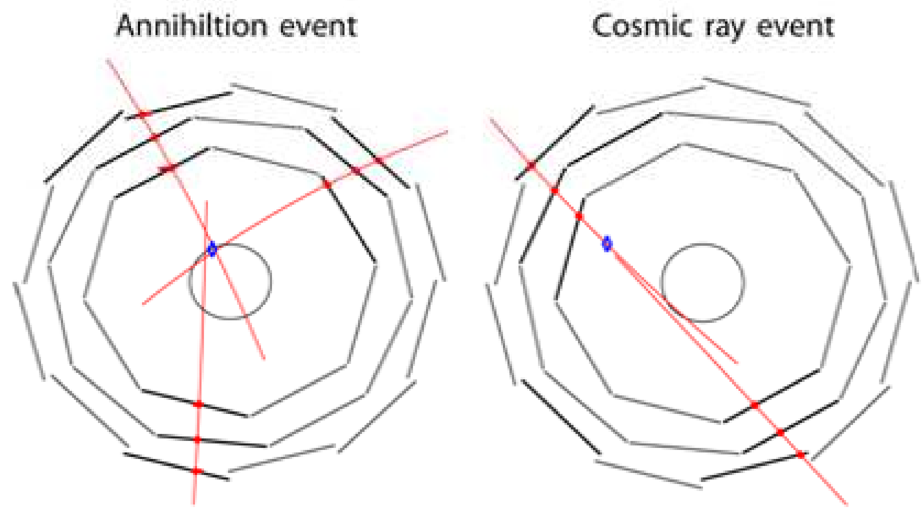
Richard Hydomako / Calgary

improving signal-to-noise ratio

- Cosmic background
  - constant rate – ~10 events per second
- Minimise read-out duration
  - Rapid neutral trap magnet shutdown → squeeze Hbar signal in time
  - IGBT switches current
  - Induces magnet quench
- Identify cosmic ray signature
  - Mostly top-to-bottom straight lines
  - Rejects vertices from co-linear tracks
  - Rejects vertices too far away from trap wall
  - Monte Carlo simulation: 99.5% rejection 1 in 709 attempts



Eoin Butler/ CERN



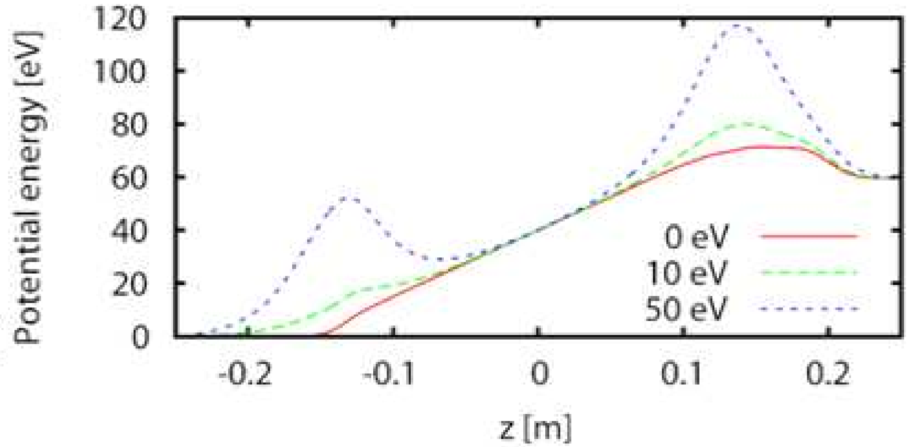
Richard Hydomako / Calgary

improving signal-to-noise ratio

- Mirror-trapped pbar

$$\underbrace{\frac{1}{2}mv_{\parallel}^2}_{\text{KE}} + \underbrace{\frac{1}{2}mv_{\perp 0}^2\frac{B}{B_0} + q\phi}_{\text{potential energy}} = \text{const}$$

  - with enough $v_{\perp 0}^2$ clearing field **will** fail

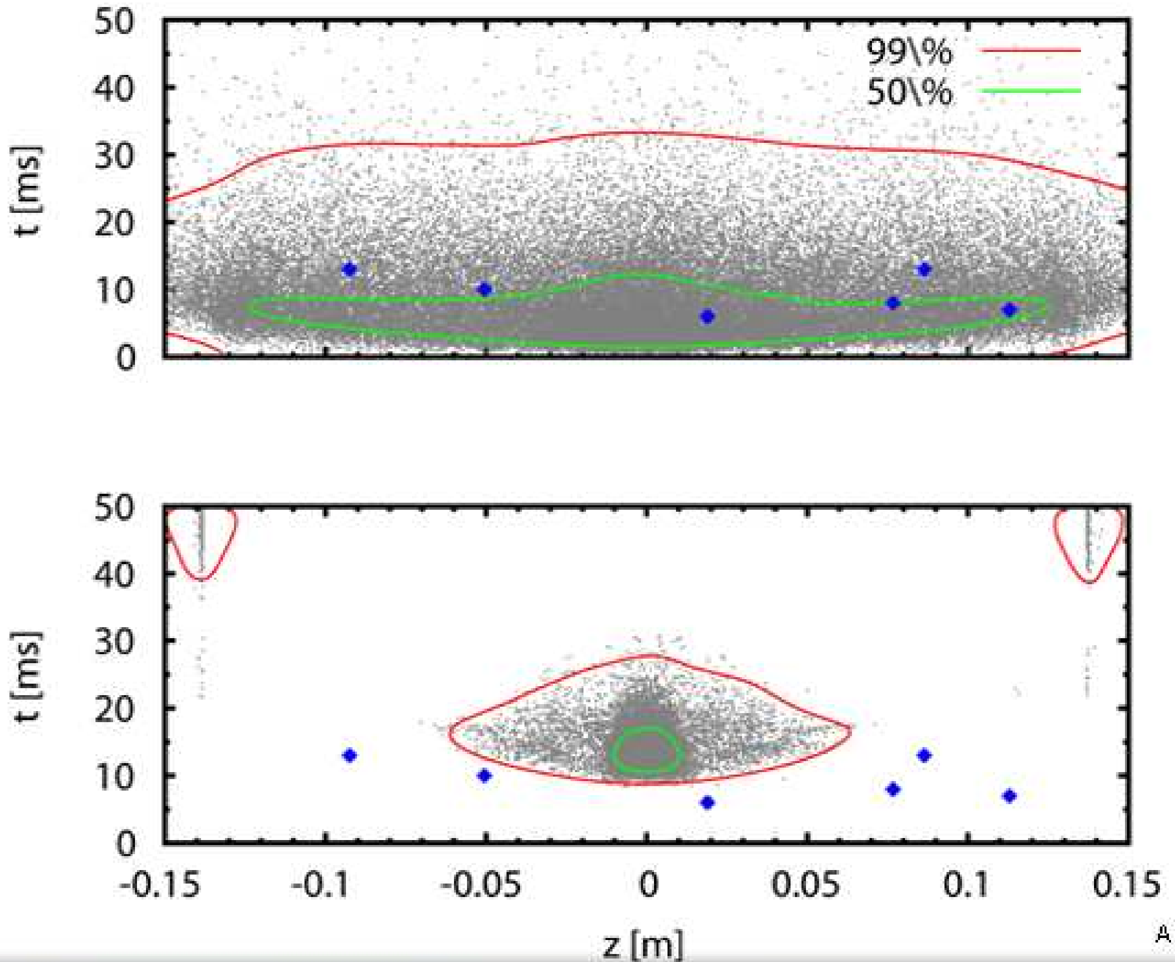


Eoin Butler/ CERN

- Is it likely?
  - No
  - Nothing in the mixing process can heat pbar to 50 eV / 600,000 K
  - Exotic species left
- How to prove empirically?
  - Monte Carlo simulation
  - "Hot mixing"
  - "quench with field"

improving signal-to-noise ratio

- Monte Carlo simulation
  - Solenoid, mirrors, octopole
  - Different dynamics for charged and uncharged species
  - Different annihilation signatures (z and t)



Andresen, et al., Phys. Lett. B 695, 95 (2011)

improving signal-to-noise ratio

- "Hot mixing"
  - Deliberately heats up plasma
  - Keep all other procedures → expects same exotics
  - No trappable Hbar
  - Result:

1 event in 246 trials

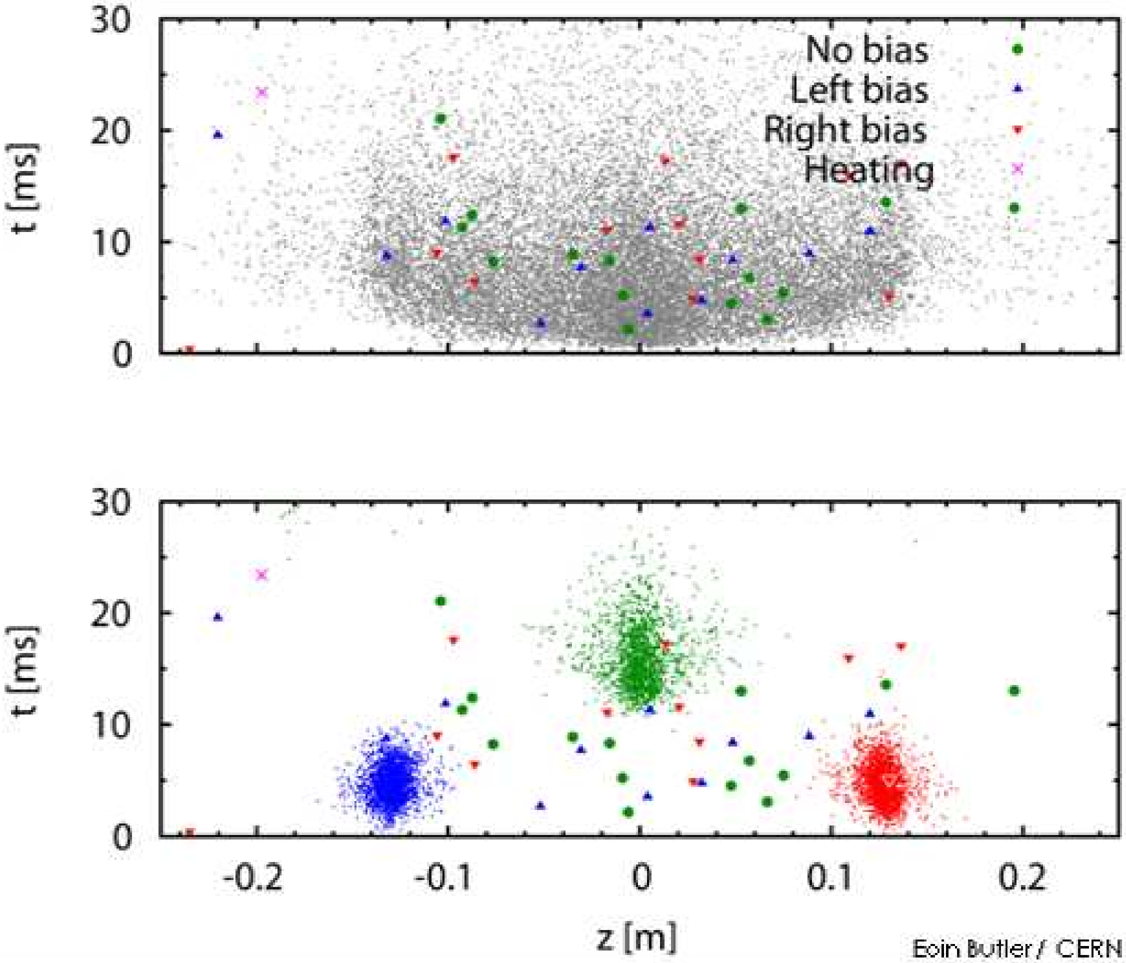
  - Compare with no heating:

38 events in 335 trials

Andresen, et al., Phys. Lett. B 695, 95 (2011)

improving signal-to-noise ratio

- "Quench with field"
  - Applies electric field while turning off neutral trap
  - Charged species should be offset
  - Compare signature of charged and uncharged species with simulation



1000 s trapping

- Published online on Nature Physics 4 days ago
- Last trapping time (Nature 2010): 172 ms
- New result:

Confinement time (s)	0.4	10.4	50.4	180	600	1,000	2,000
Number of attempts	119	6	13	32	12	16	3
Detected events	76	6	4	14	4	7	1
Estimated background	0.17	0.01	0.02	0.05	0.02	0.02	0.004
σ	>>20	8.0	5.7	11	5.8	8.0	2.6
Trapping rate	1.13 ± 0.13	1.76 ± 0.72	0.54 ± 0.26	0.77 ± 0.21	0.59 ± 0.29	0.77 ± 0.29	0.59 ± 0.59

1000 s trapping

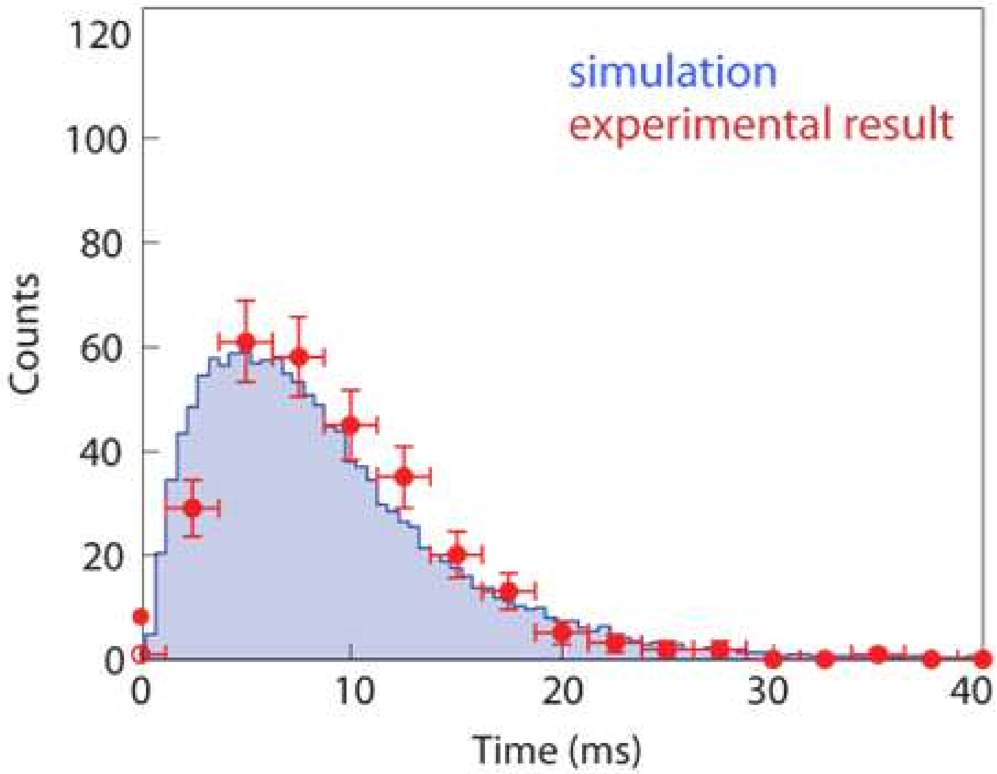
- Annihilation signature analysis
  - Compare z and t distribution with simulation

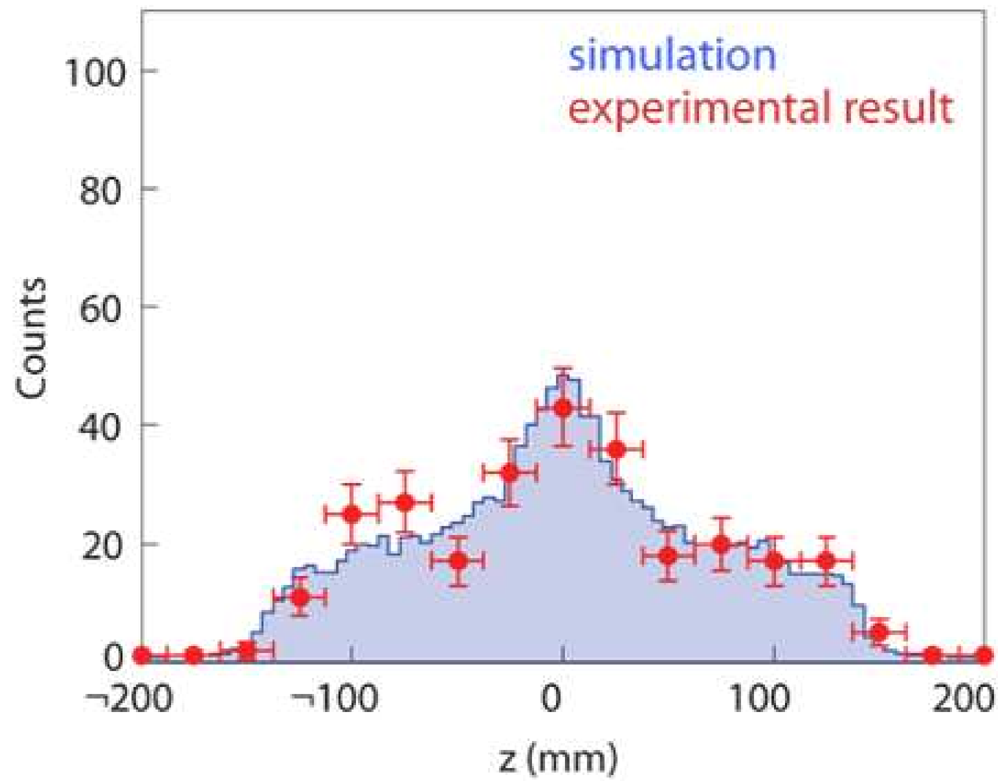
- Simulation
  - Assume trapped Hbar comes from the tail of much higher temperature distributions

$$f_{\overline{H}}(E) \propto \sqrt{E}$$

  - All other IC are random
    (subject to physical dimensions of trap and production method)

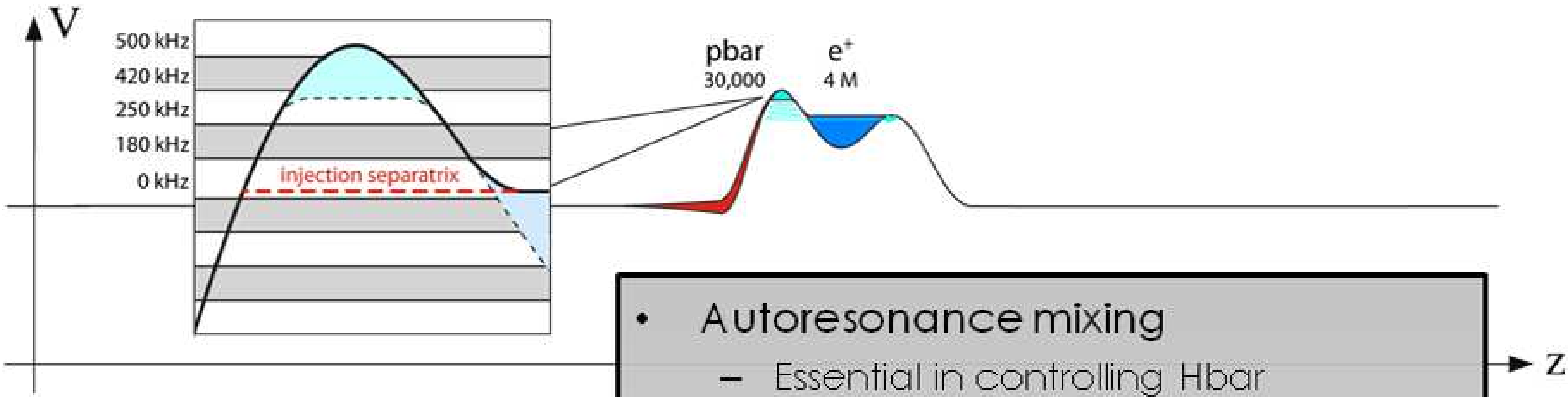
1000 s trapping

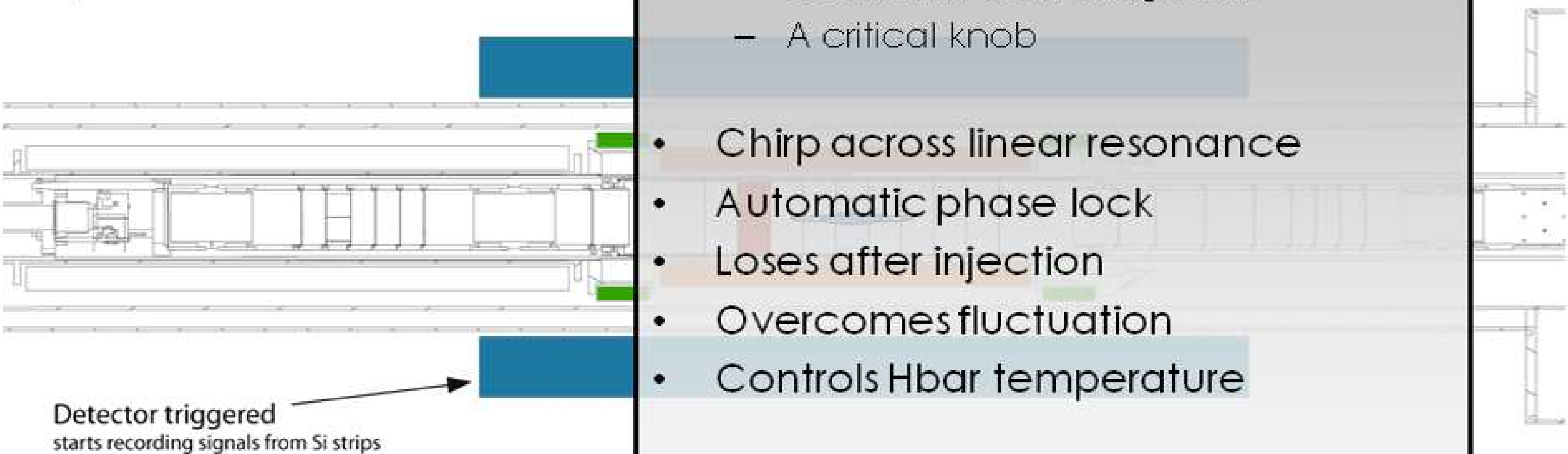




Andresen, et al., Nat. Phys. 2011/06/05/online
doi:10.1038/nphys2025

Autoresonance mixing simulation

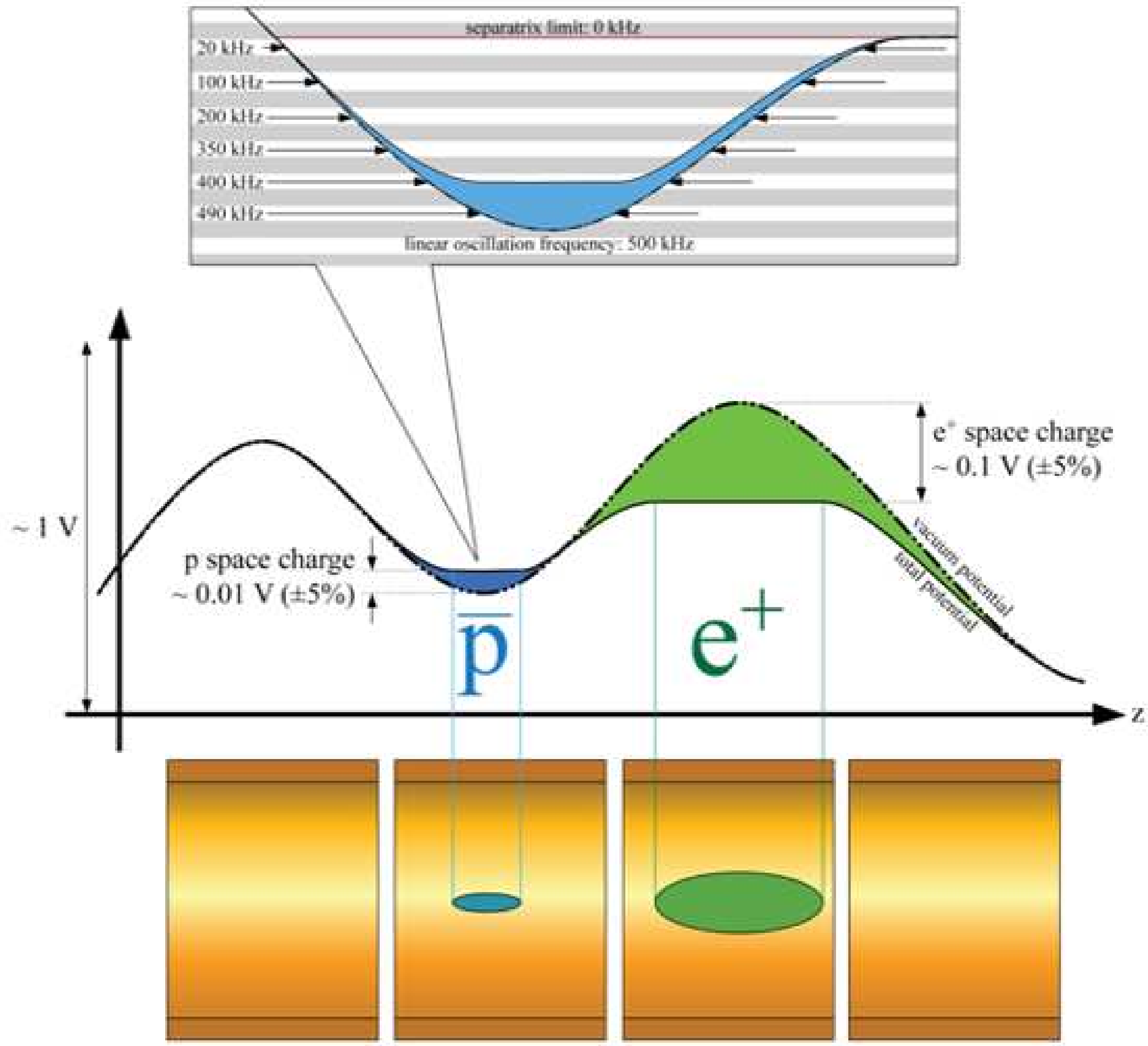




- Autoresonance mixing
  - Essential in controlling Hbar
  - A critical knob
- Chirp across linear resonance
- Automatic phase lock
- Loses after injection
- Overcomes fluctuation
- Controls Hbar temperature

Autoresonance mixing simulation

- Time scale problem
  - pbar bounce frequence
  - positron much faster
    → quasi-static limit
    → Poisson-Boltzmann
  - pbar motion
    → fully time dependent
    → Vlasov-Poisson
  - collision
    → Fokker-Planck



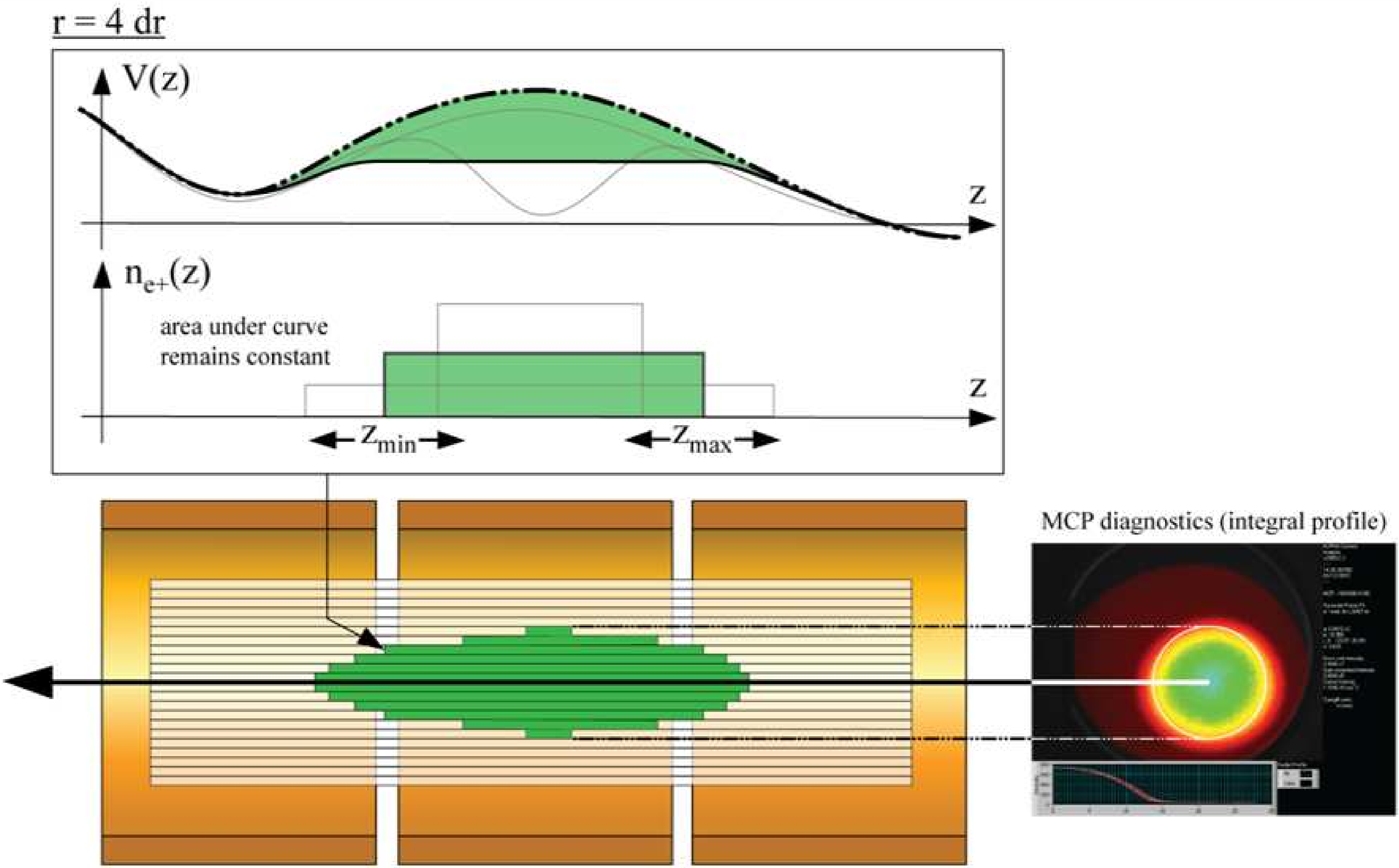
0K Poisson-Boltzmann solver

$$\nabla^2\phi(r,z)=\frac{q}{\varepsilon_0}n(r,z)$$

$$n(r,z)=n_0(r)e^{-\frac{q}{k_B T}\phi(r,z)}$$

- Numerical problem at low T

0K Poisson-Boltzmann solver

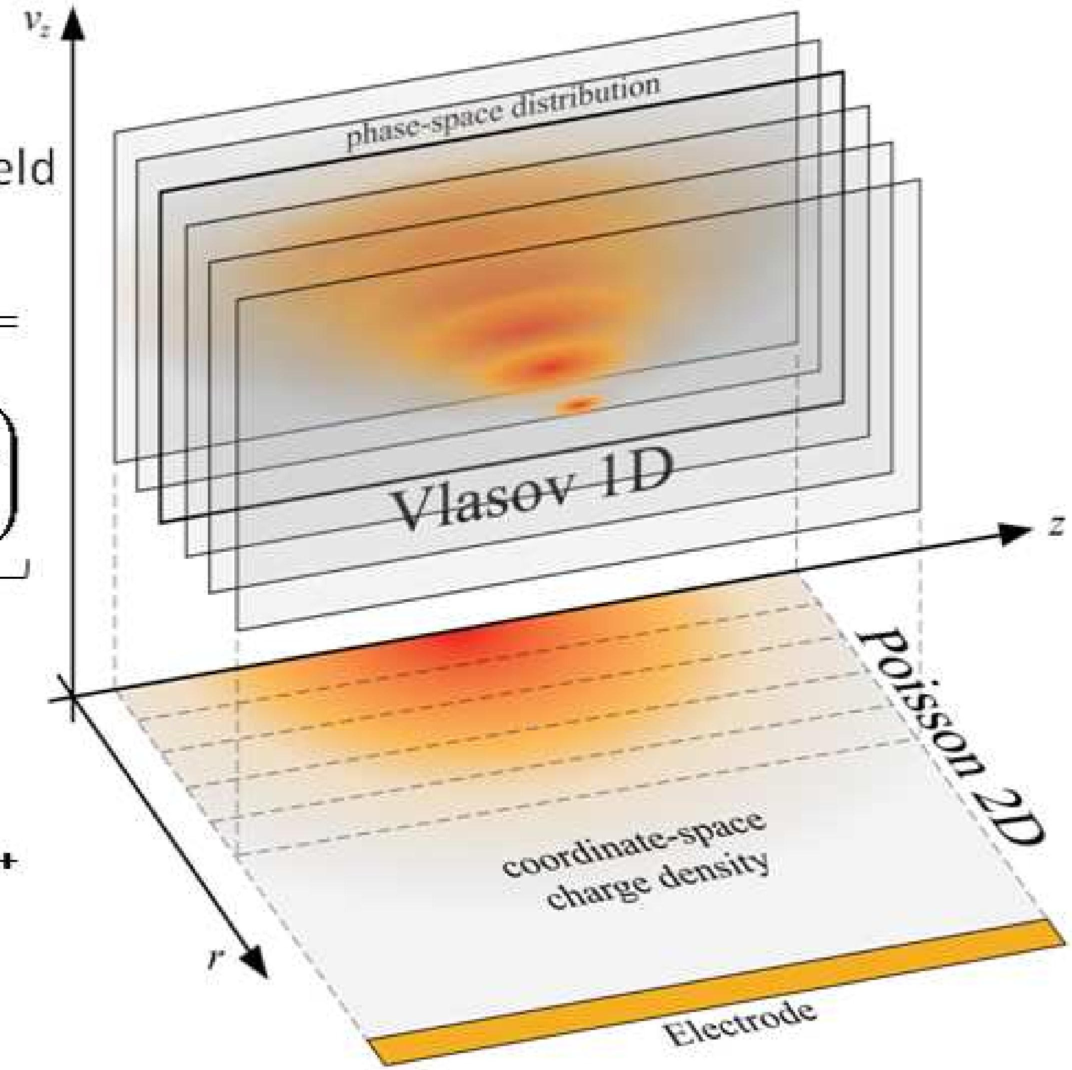


Vlasov-Poisson solver

- Strong solenoidal field → no radial transport
- 1D Vlasov-Poisson equation with Fokker-Planck terms:

$$\frac{\partial f}{\partial t} + \overbrace{v_z \frac{\partial f}{\partial z}}^{\text{move by v}} \overbrace{- \frac{q}{m}\frac{\partial \phi}{\partial z}\frac{\partial f}{\partial v_z}}^{\text{acc. by E field}} = \underbrace{-\frac{\partial}{\partial v_z}\left(\left\langle \frac{\Delta v_z}{\Delta t} \right\rangle f\right)}_{\text{FP drift}} + \underbrace{\frac{1}{2}\frac{\partial^2}{\partial v_z^2}\left(\left\langle \frac{\Delta v_z \Delta v_z}{\Delta t} \right\rangle f\right)}_{\text{FP diffusion}}$$

$$\nabla^2 \phi = \frac{e}{\varepsilon_0}\sigma \int f dv_z - \frac{e}{\varepsilon_0} n_{e+}$$



Vlasov-Poisson solver

- Vlasov equation

$$\frac{\partial f}{\partial t}+\boxed{v_z\frac{\partial f}{\partial z}}-\boxed{\frac{q}{m}\frac{\partial \phi}{\partial z}\frac{\partial f}{\partial v_z}}=\boxed{-\frac{\partial}{\partial v_z}\left(\left\langle\frac{\Delta v_z}{\Delta t}\right\rangle f\right)}+\boxed{\frac{1}{2}\frac{\partial^2}{\partial v_z^2}\left(\left\langle\frac{\Delta v_z \Delta v_z}{\Delta t}\right\rangle f\right)}$$

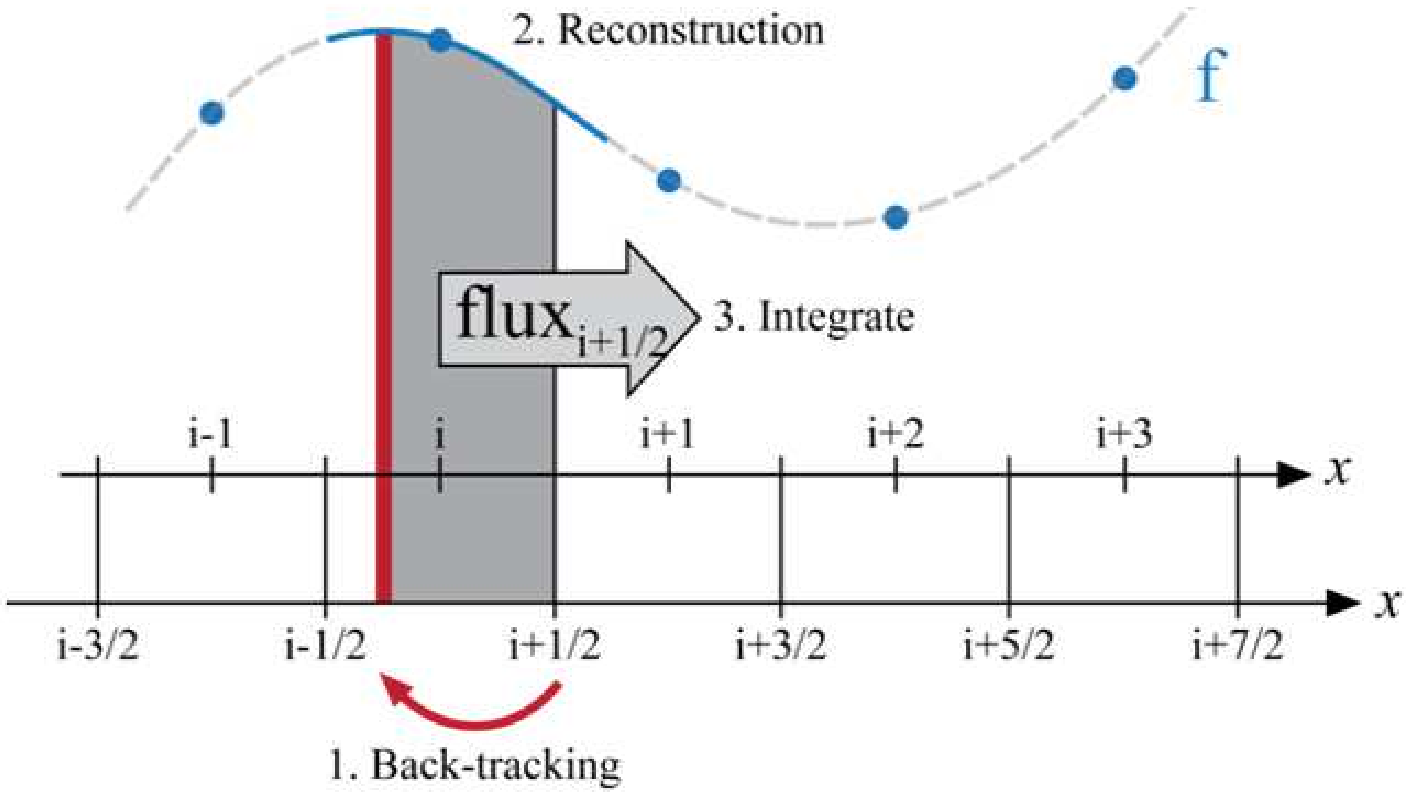
all in the form of

$$\frac{\partial f(x,t)}{\partial t}+\frac{\partial}{\partial x}\left(u(x,t)f(x,t)\right)=0$$

- Operator splitting → 3 advections, 1 diffusion
- Discretise advection operator

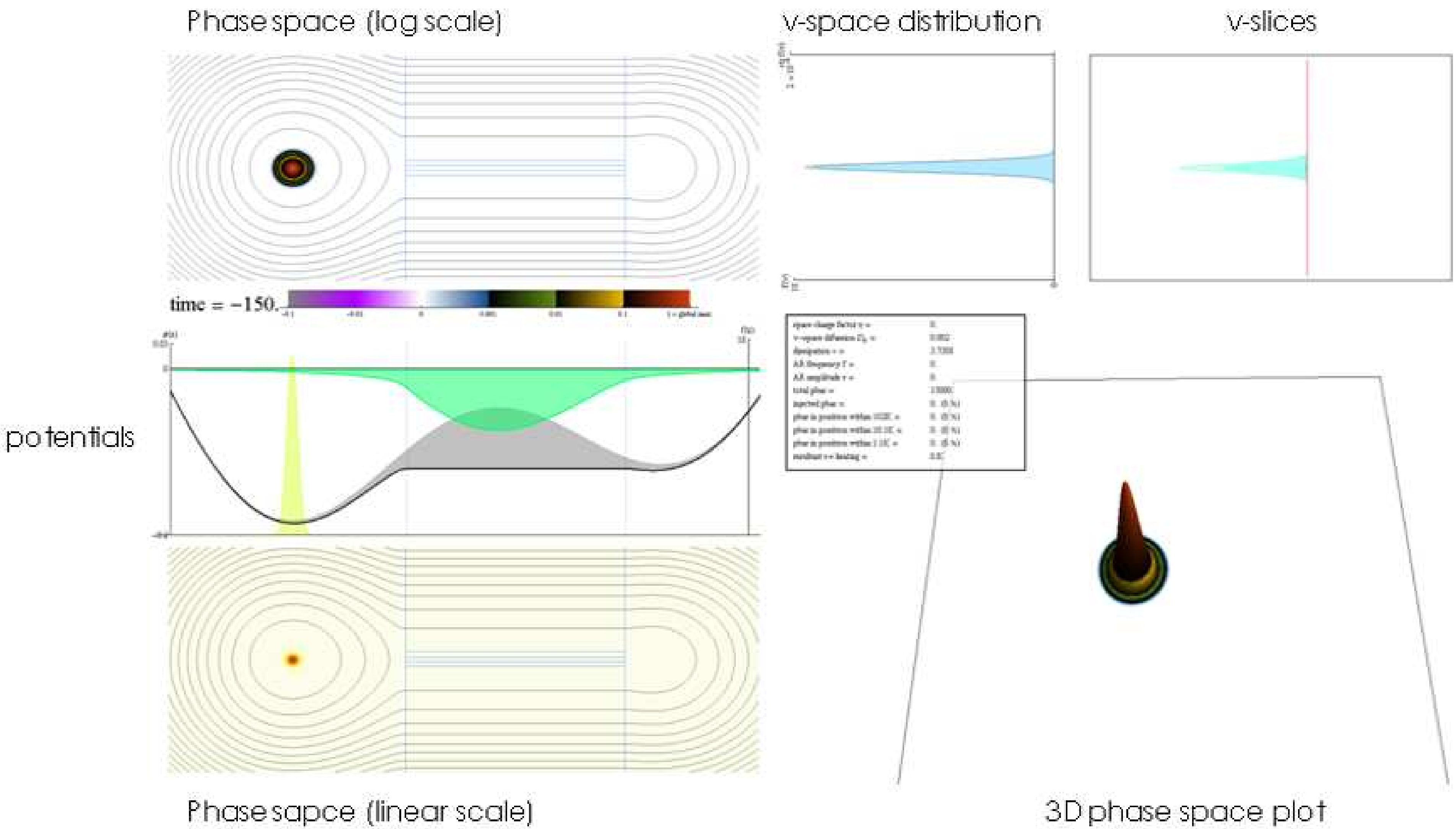
Vlasov-Poisson solver

- Flux balanced method
  - What comes out from one cell must end up in the next
  - How much: method of characteristic



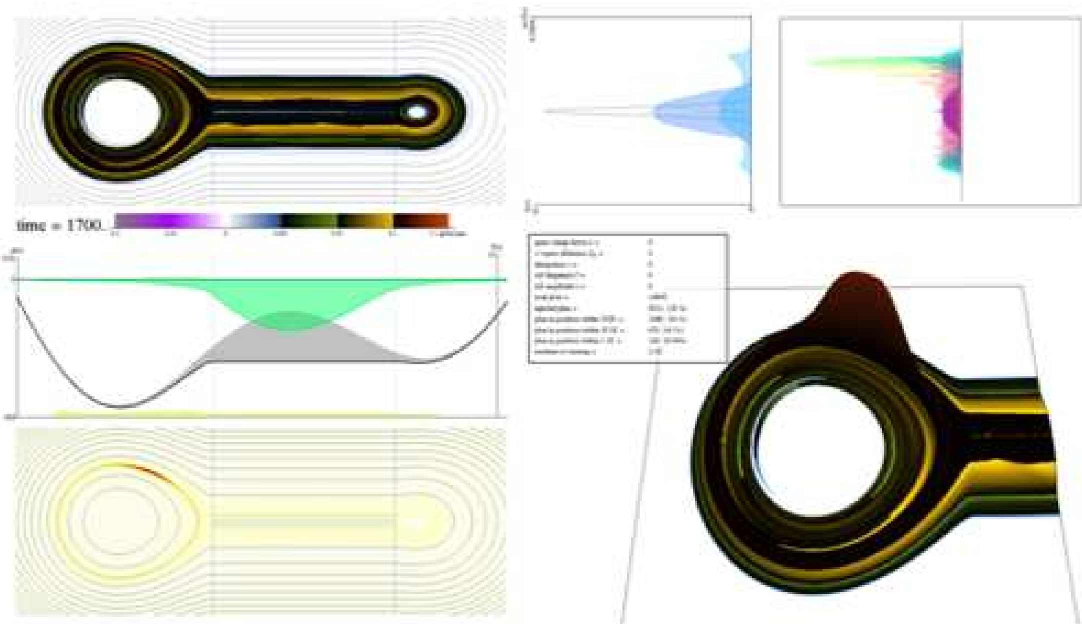
- Reconstruction!!

movie


Phase space (log scale)
v-space distribution
v-slices
time = −150.
potentials
Phase sapce (linear scale)
3D phase space plot

Autoresonance mixing simulation

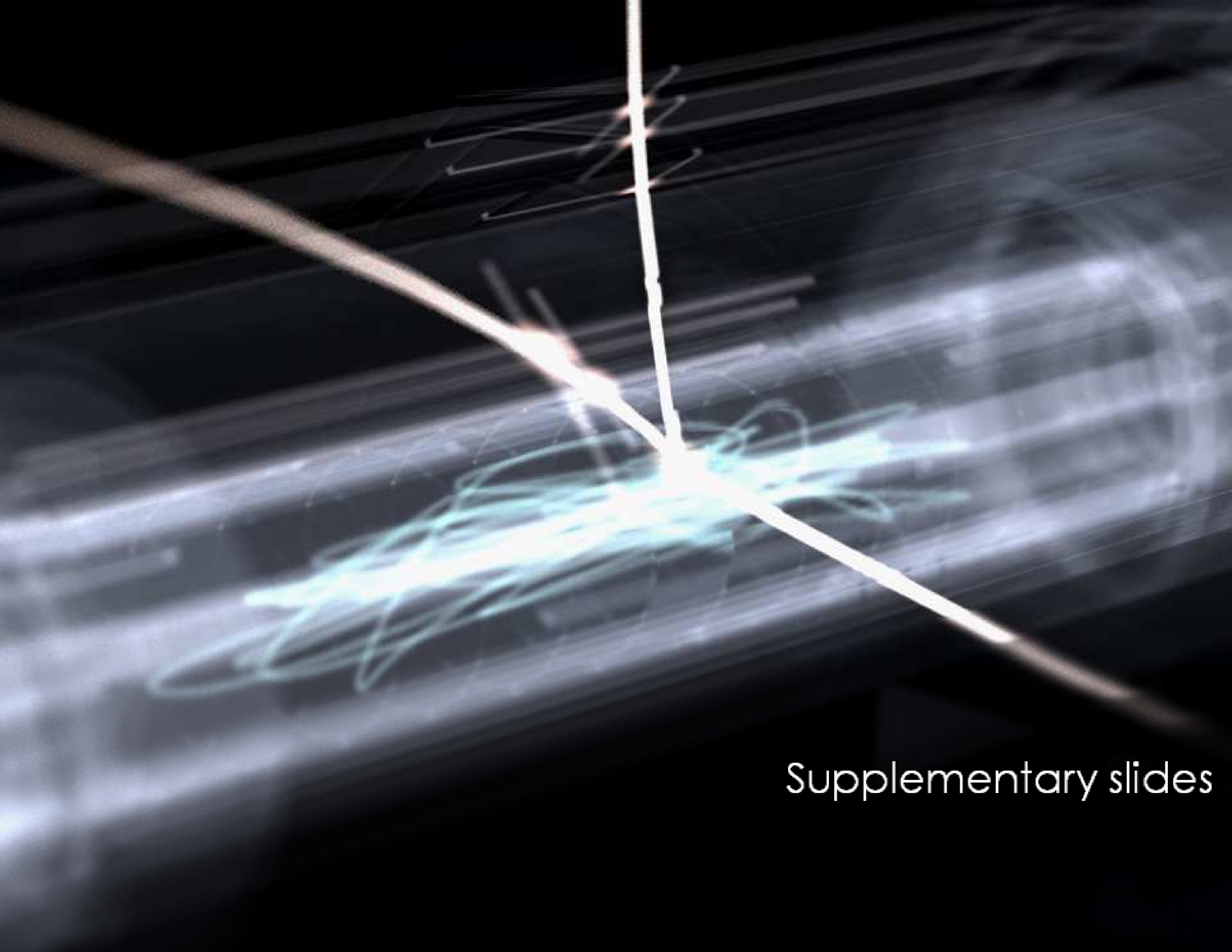
- Autoresonance mixing
  - Essential in controlling Hbar
  - A critical knob
- A powerful tool
- Next...
  - More speed!
  - Compare existing and new data
  - Understand
  - Improve
  - Other plasma dynamics



the next step

- Last year:
  - First ever trapped antihydrogen
  - 309 Hbar trapped in total
  - 1000 s holding time
  - First energy measurement
- This year:
  - Improve Hbar production
  - First physics measurement microwave hyperfine
- Near future:
  - ALPHA-II
  - Laser measurement

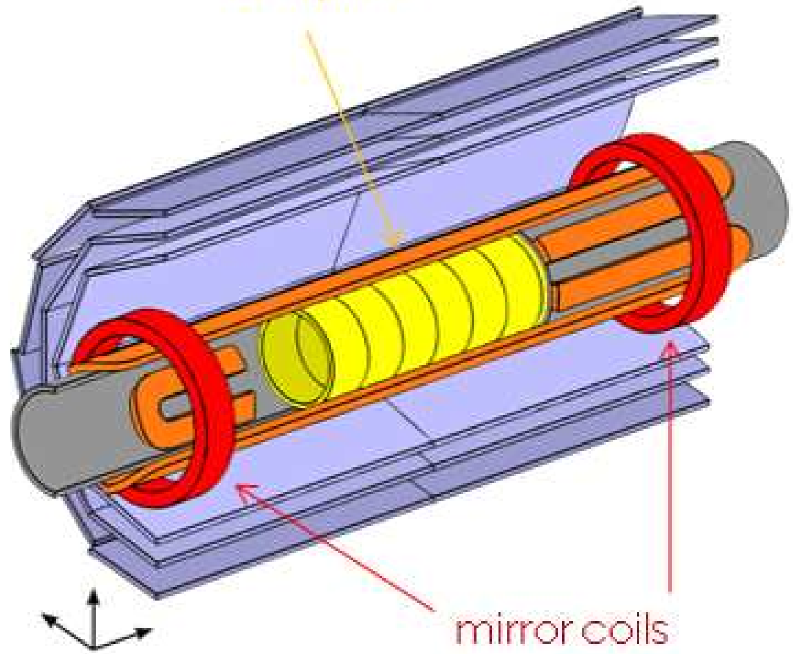
End

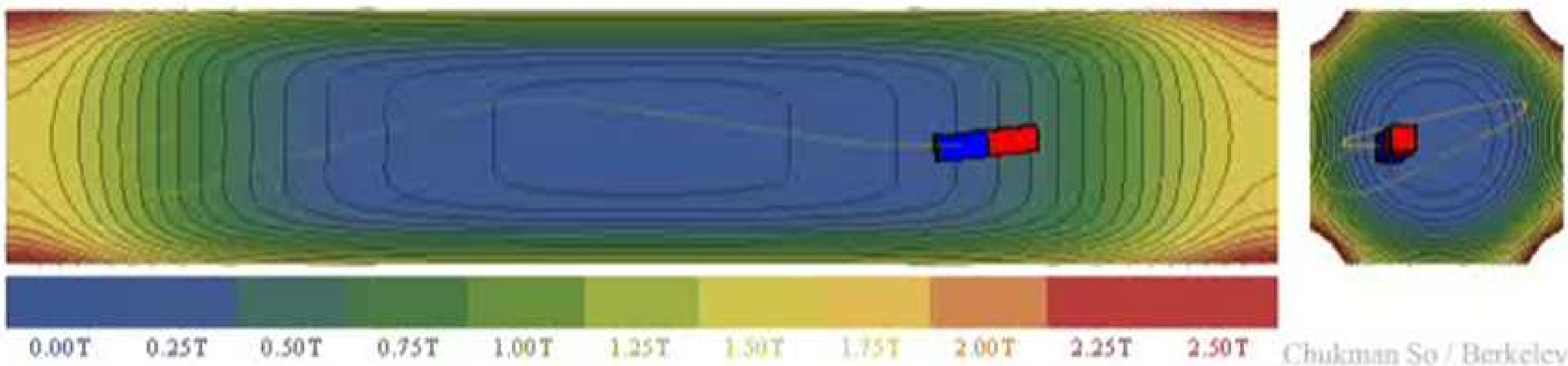


Supplementary slides

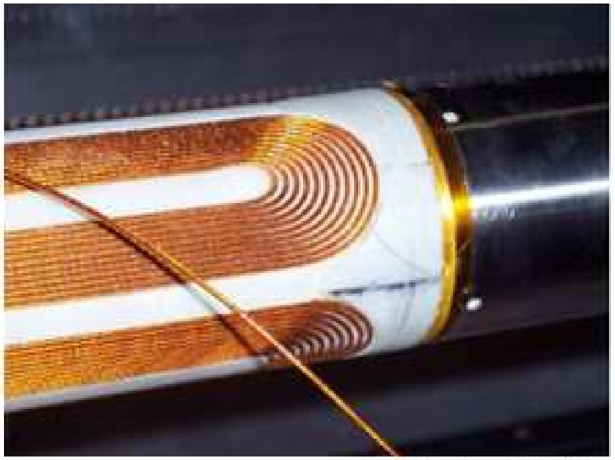
trapping neutral antimatter

- No contact with matter
  - Ultra high vacuum
  - Magnetic minimum trap
- Axial confinement: mirror coils
- Radial confinement: multipole magnet

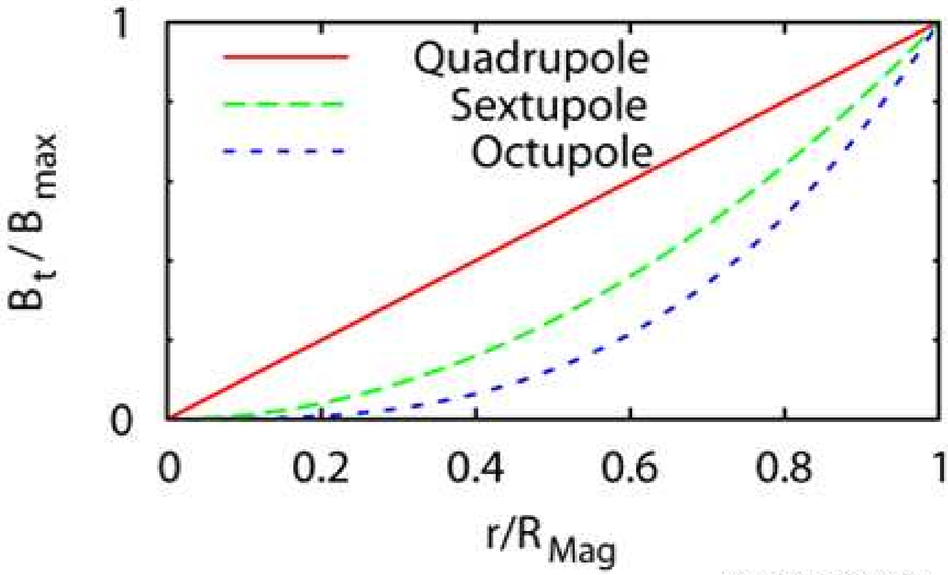




- Which order to choose?
  - Higher order: minimise field near axis
  - Lower order: simpler construction, thicker wire bundle
  - Balance in ALPHA: octopole
- Avoid phantom mirrors: staggered racetrack



Eoin Butler / CERN



Eoin Butler / CERN

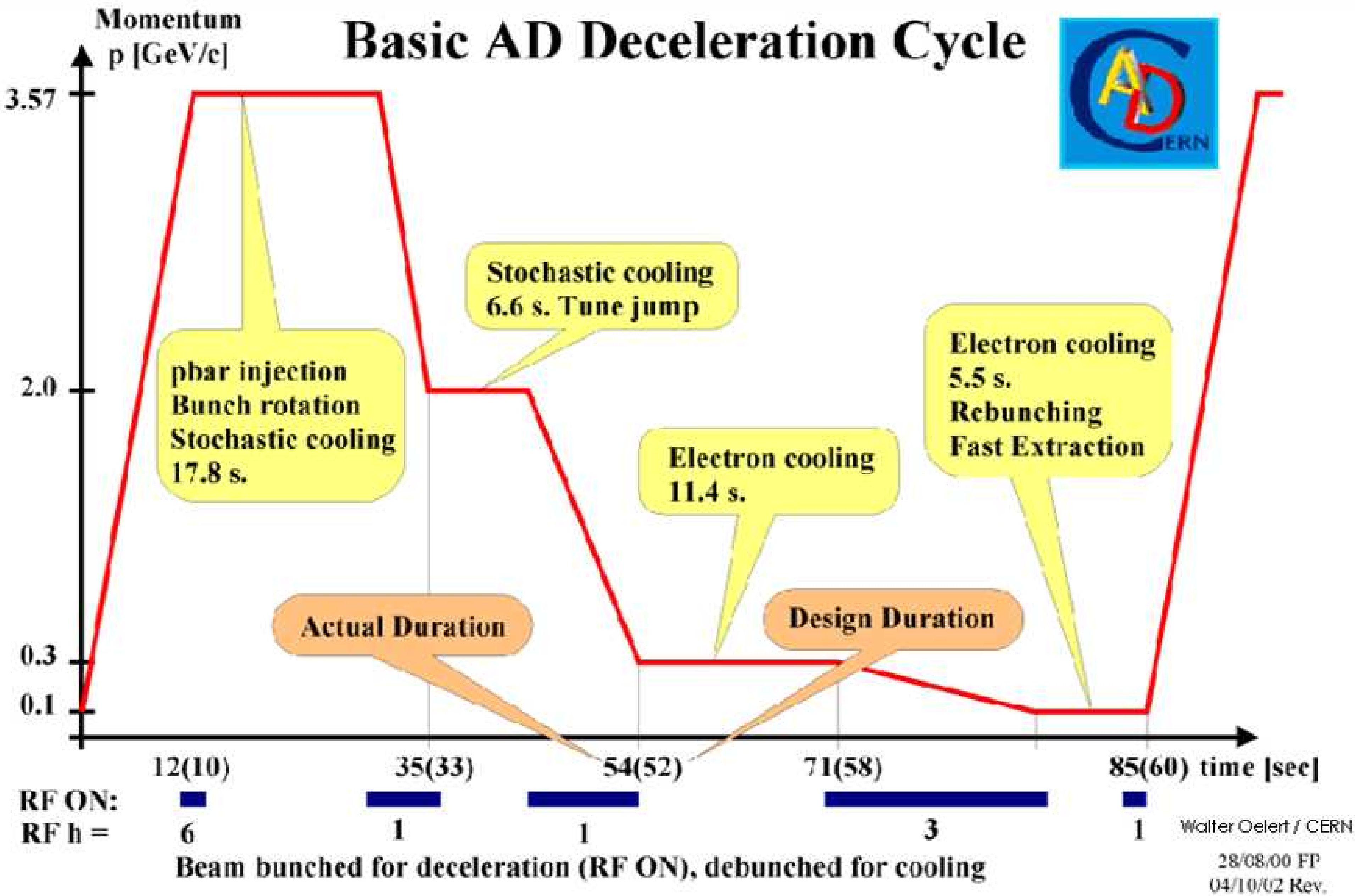
the Antiproton Decelerator

- Cycled operation:
  - 85 – 100 s per cycle, 24 h operation for 6 - 7 months a year
- Production
  - 26 GeV, 1.5E+13 proton from the PS
  - Tungsten target → 3.57 GeV, 5E+07 pbar
- Capture and injection
- Deceleration and cooling

P GeV/c	Transverse Emittances in p mm.mrad Before	After	Momentum Spread in % Before	After	Cooling time in s	Cooling process
3.57	200	5	1.5	0.1	20	Stochastic
2.0	9	5	0.18	0.03	15	Stochastic
0.3	33	2	0.2	0.1	6	Electron
0.1	6	1	0.3	0.01	1	Electron
0.1 bunched	-	1	-	0.1	-	Electron

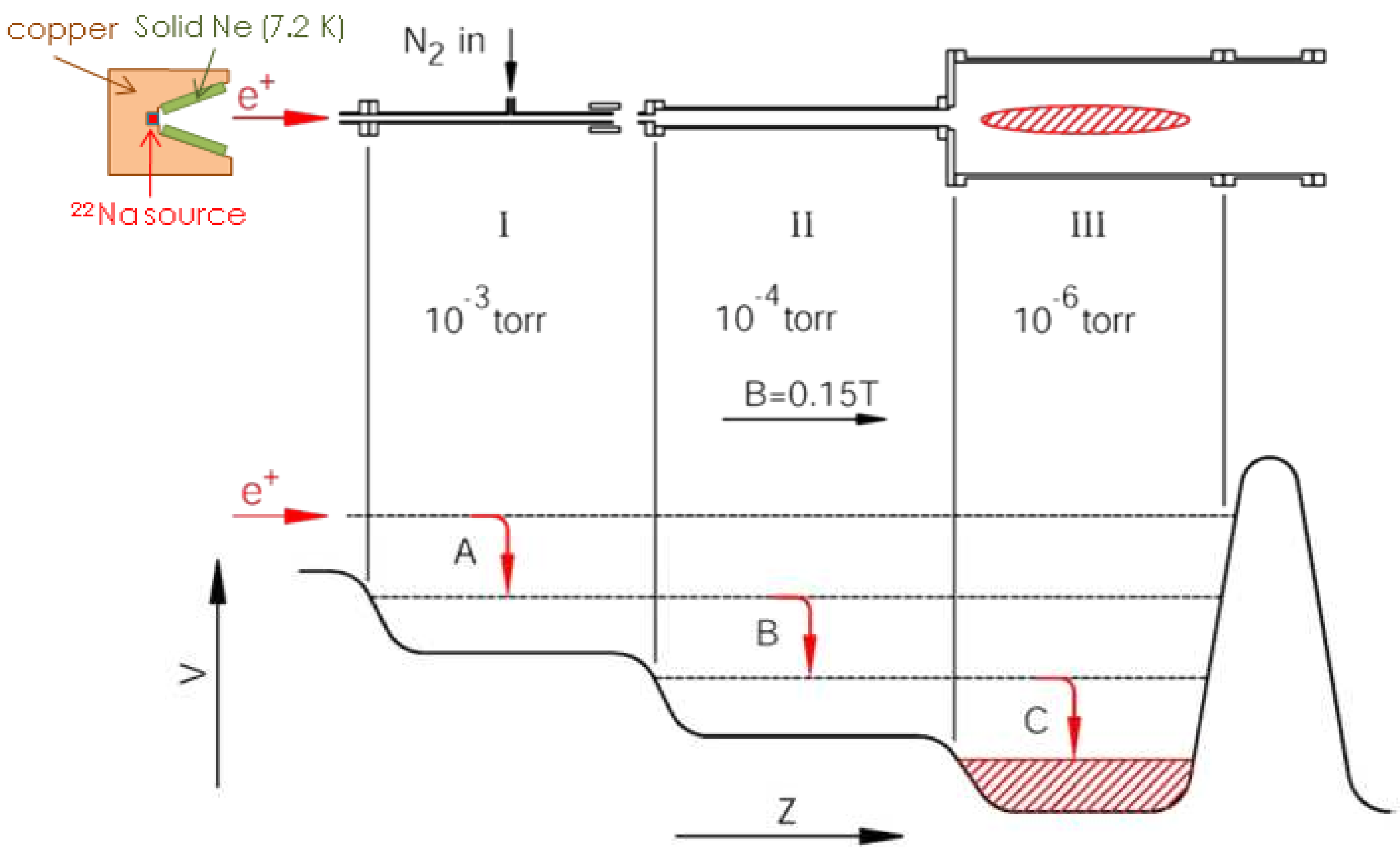
- Pulsed extraction
  - 100 MeV, 1.2E+07 pbar in 200 – 500 ns pulse

the Antiproton Decelerator



the Positron Accumulator

- Na-22 source → 1E+07 e^+/s, ~100 keV
- Solid-Neon modulator → 1E+06 e^+/s, ~1 eV
- Buffer gas N2 cooling → 2E+07 e^+/ 150 s, ~25 meV (300 K)



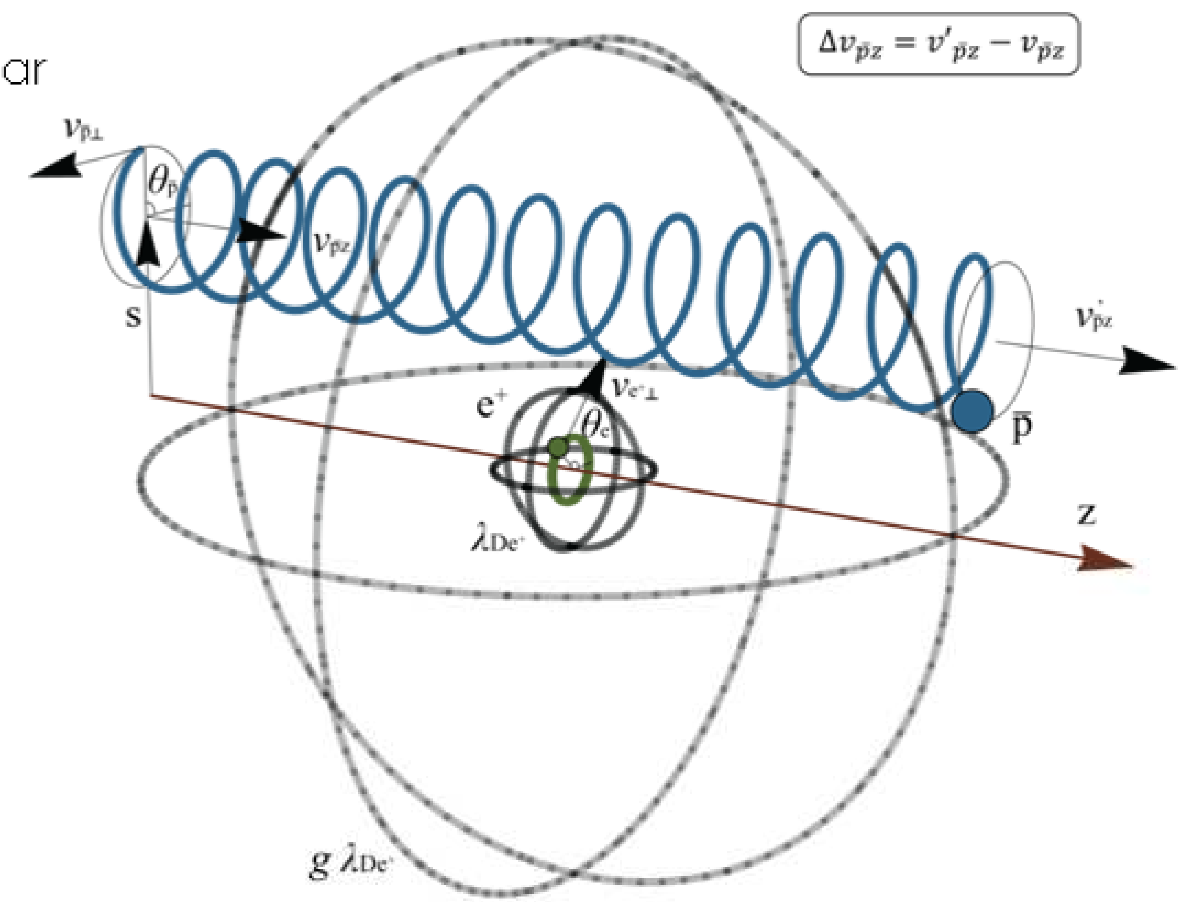
Cliff Surko / San Diego

Fokker-Planck coefficients

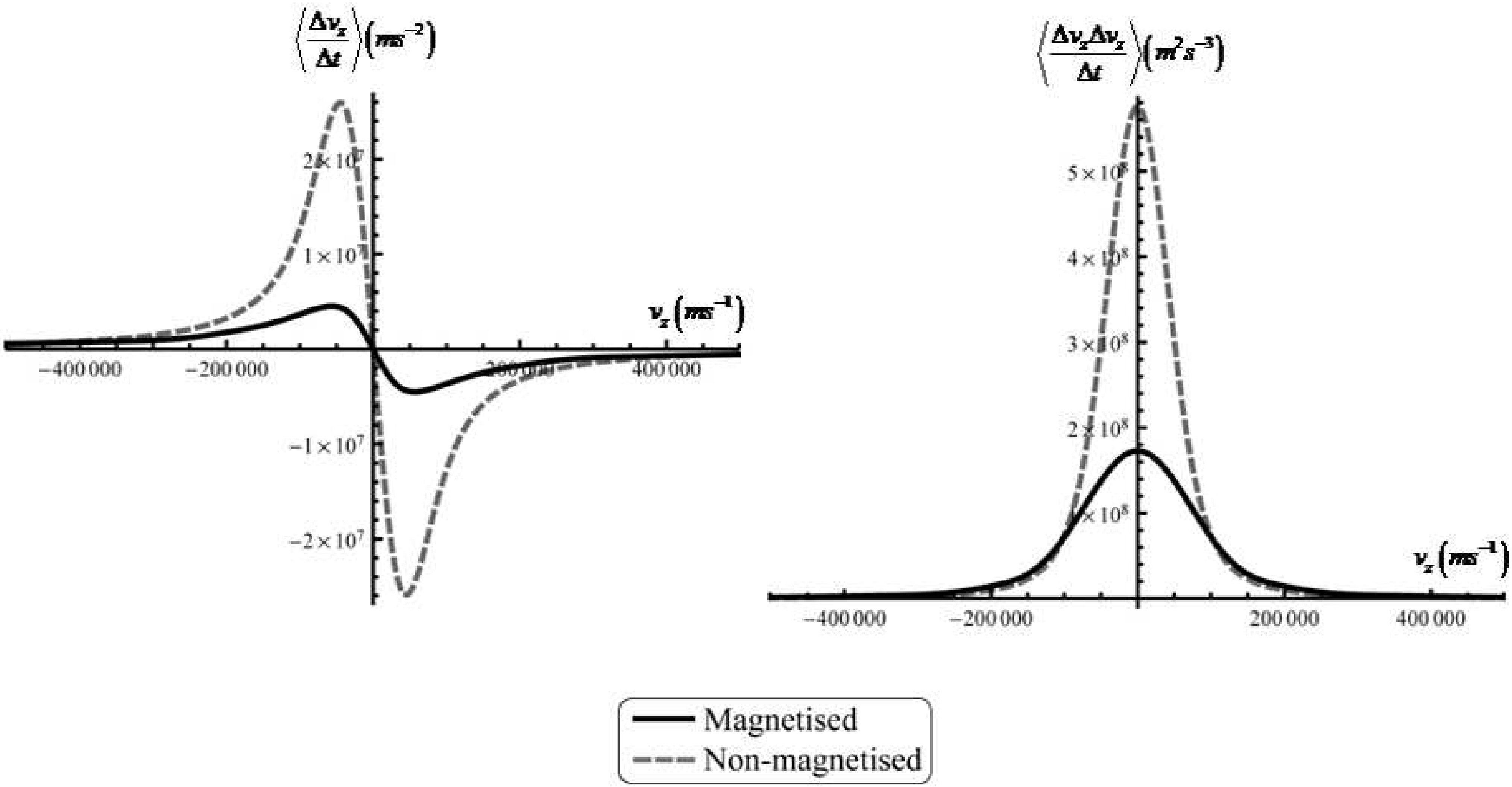
- Drift and diffusion coefficients

$$-\frac{\partial}{\partial v_z}\left(\left\langle\frac{\Delta v_z}{\Delta t}\right\rangle f\right)+\frac{1}{2}\frac{\partial^2}{\partial v_z^2}\left(\left\langle\frac{\Delta v_z \Delta v_z}{\Delta t}\right\rangle f\right)$$

- z-axis only
- Binary collision model
  - Δv_z : change of v when pbar passes a positron
  - Δt : how often
  - $\langle\ \rangle$: averaged over all IC
  - as a function of



Fokker-Planck coefficients



Vlasov-Poisson solver

- Reconstruction methods
  - linear reconstruction

$$f(x) = f_i + (f_{i+1} - f_{i-1})\frac{x - x_i}{2\Delta x} \qquad x \in [x_{i-1/2}, x_{i+1/2})$$

  - Positive flux conserving method

$$\begin{aligned} f(x) &= f_i + \epsilon_i^+ (f_{i+1} - f_i)\frac{2(x - x_i)(x - x_{i-3/2}) + (x - x_{i-1/2})(x - x_{i+1/2})}{6\Delta x^2} \\ &\quad + \epsilon_i^- (f_i - f_{i-1})\frac{2(x - x_i)(x - x_{i+3/2}) + (x - x_{i-1/2})(x - x_{i+1/2})}{6\Delta x^2} \qquad x \in [x_{i-1/2}, x_{i+1/2}) \\ \epsilon_i^+ &= \begin{cases} min\left(1, 2\dfrac{f_i}{f_{i+1} - f_i}\right) & f_{i+1} - f_i > 0 \\ min\left(1, -2\dfrac{f_{max} - f_i}{f_{i+1} - f_i}\right) & f_{i+1} - f_i < 0 \end{cases} \\ \epsilon_i^- &= \begin{cases} min\left(1, 2\dfrac{f_{max} - f_i}{f_i - f_{i-1}}\right) & f_i - f_{i-1} > 0 \\ min\left(1, -2\dfrac{f_i}{f_i - f_{i-1}}\right) & f_i - f_{i-1} < 0 \end{cases} \end{aligned}$$

Vlasov-Poisson solver

- Reconstruction methods
  - piecewise parabolic method

$$f(x) = f_i^L + \frac{x - x_{i-1/2}}{\Delta x}\left((f_i^R - f_i^L) + 6\left(f_i - \frac{f_i^R + f_i^L}{2}\right)\left(1 - \frac{x - x_{i-1/2}}{\Delta x}\right)\right) \qquad x \in [x_{i-1/2}, x_{i+1/2})$$

$$\text{where}\left\{\begin{array}{l}
f_i^L = f_{i-1/2} \text{ and } f_i^R = f_{i+1/2} \\
f_{i+1/2} = \dfrac{f_i + f_{i+1}}{2} - \dfrac{1}{6}(S_{i+1} - S_i) \\
S_i = \left\{\begin{array}{ll} \operatorname{sgn}\left(\dfrac{f_{i+1} - f_{i-1}}{2}\right)\min\left(\left|\dfrac{f_{i+1} - f_{i-1}}{2}\right|, 2\left|f_{i+1} - f_i\right|, 2\left|f_i - f_{i-1}\right|\right) & (f_{i+1} - f_i)(f_i - f_{i-1}) > 0 \\ 0 & \text{otherwise} \end{array}\right. \\
\left\{\begin{array}{ll}
\text{if } (f_i^R - f_i)(f_i - f_i^L) \le 0, & f_i^L \to f_i,\ f_i^R \to f_i \\
\text{if } (f_i^R - f_i^L)\left(f_i - \dfrac{f_i^L + f_i^R}{2}\right) > \dfrac{(f_i^R - f_i^L)^2}{6}, & f_i^L \to 3f_i - 2f_i^R \\
\text{if } (f_i^R - f_i^L)\left(f_i - \dfrac{f_i^L + f_i^R}{2}\right) < -\dfrac{(f_i^R - f_i^L)^2}{6}, & f_i^R \to 3f_i - 2f_i^L
\end{array}\right.
\end{array}\right.$$

Vlasov-Poisson solver

- Reconstruction methods
  - uniformly non-oscillatory method

$$f(x) = f_i + S_i \frac{x - x_i}{\Delta x} \qquad x \in [x_{i-1/2}, x_{i+1/2})$$

$$\text{where} \begin{cases} S_i = \text{minmod}\left(f_t'(x \to x_i^-), f_t'(x \to x_i^+)\right) \\ f_t(x) = f_i + (f_{i+1} - f_i)\frac{x - x_i}{\Delta x} + \frac{1}{2} D_{i+1/2} \frac{(x - x_i)(x - x_{i+1})}{\Delta x^2} \qquad x \in [x_i, x_{i+1}] \\ D_{i+1/2} = \text{minmod}(D_i, D_{i+1}) = \begin{cases} \text{sgn}(D_i)\min(|D_i|, |D_{i+1}|) & \text{sgn}(D_i) = \text{sgn}(D_{i+1}) \\ 0 & \text{otherwise} \end{cases} \\ D_i = f_{i+1} + f_{i-1} - 2f_i \end{cases}$$

  - essentially non-oscillatory method
  - barycentric interpolation
  - etc etc