Precision physics and antimatter

Summary – Day 1

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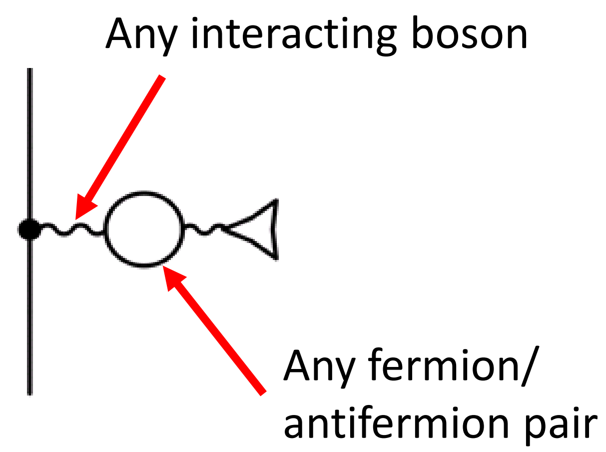
- Precision experiments are a complementary way of searching new physics

$$\frac{g_{electron}}{2} = 1 + a_{QED} + a_{\mu,\tau} + a_{weak} + a_{hadrons} + a_{New\ physics}$$



Summary – Day 1

- Comparing properties of conjugate particle-antiparticle pairs provide stringent tests of CPT symmetry
- Which process gave raise to the baryongenesis in the early universe?
- Search for CPT-violating interactions

$$(i\gamma^\mu \partial_\mu - a_\mu \gamma^\mu - b_\mu \gamma_5 \gamma^\mu - m)\psi = 0$$

- Frequency difference in transitions involving spin transitions for fermion pairs
- Diurnal oscillations of observables

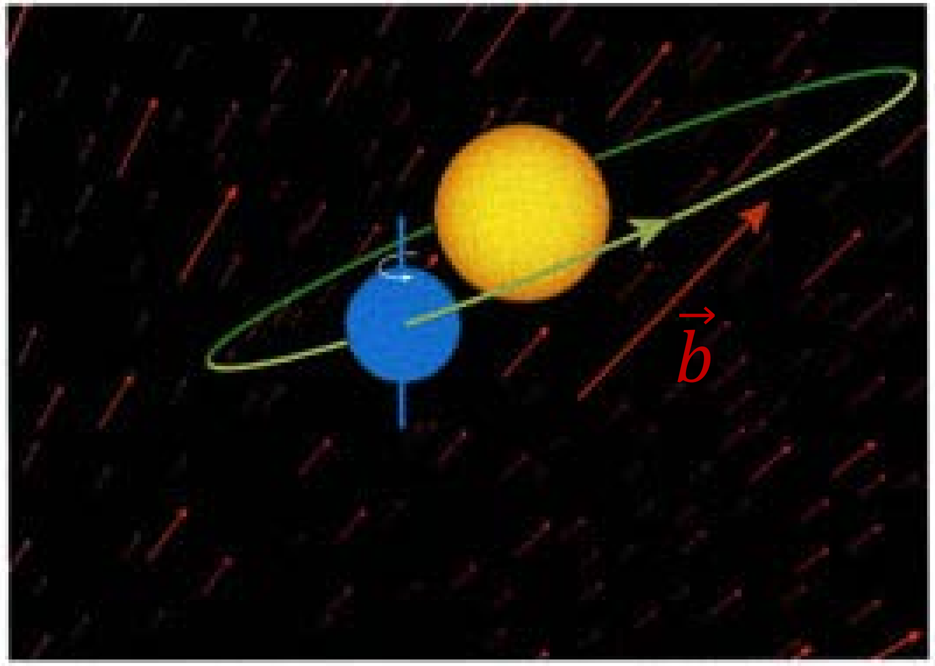


Figure from V.A. Kostelecky

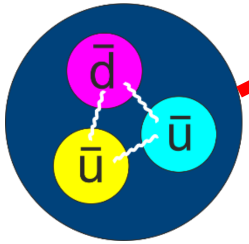
Some questions that were asked...

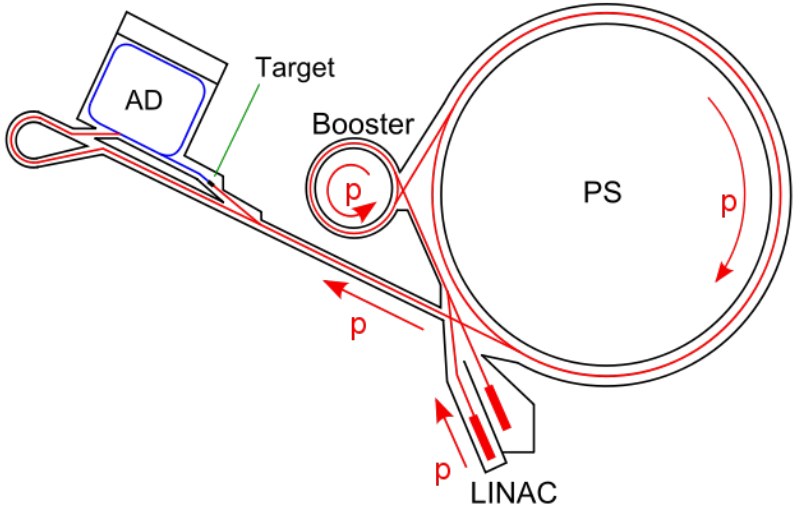
- Why should the CPT-odd fields be fixed in space?
  - Answer: It is an assumption by theory, which has to be experimentally tested.
  - It is a plausible assumption if you consider an analogy to the isotropic cosmic microwave background (CMB). CMB is a boson field (photons) which was released when the universe became transparent for photons (kT < 13.5 eV, hydrogen ionization energy). In analogy a “heavy boson field”, making up the Standard Model Extension Field b, which is weakly interacting with matter could have been emitted in the early universe. The SME fields correspond in the quantum field theory picture to bosons which mediate an unknown CPT-odd force to fermions (electrons, protons, etc.)
  - The CMB looks like a black-body radiation with ~2.7 K temperature. It is isotropic with 10^-4 fluctuations reflecting temperature fluctuations in the thermal equilibrium in the early universe. If the “heavy boson field” reflects the same amount of fluctuations it is reasonable to assume the the SME fields have a rather constant value on the trajectory of the earth.
- If CP-violation is small, and if CPT-violation makes – if it exists at all – an even smaller contribution, how can it possibly explain the Baryon asymmetry?
  - Answer: Baryon excess generation via CP violation can only take place in thermal non-equilibrium, whereas baryon excess via CPT-violation can be permanently generated also in thermal equilibrium.
  - The contribution of this process can be hardly estimated without knowing the mechanism generating CPT-violation. The quantum field theories we know come with a wide range of coupling constants and masses, therefore a baryogenesis from CPT-violation based on the current measured constraints is not excluded.

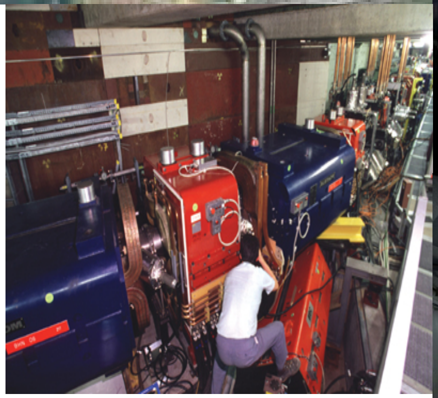
Precision physics and antimatter

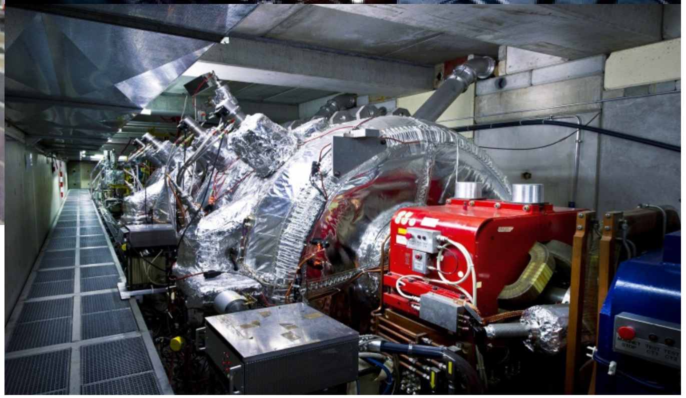
Part 2.1 Production and confinement of cold antiparticles

The Antiproton Decelerator of CERN

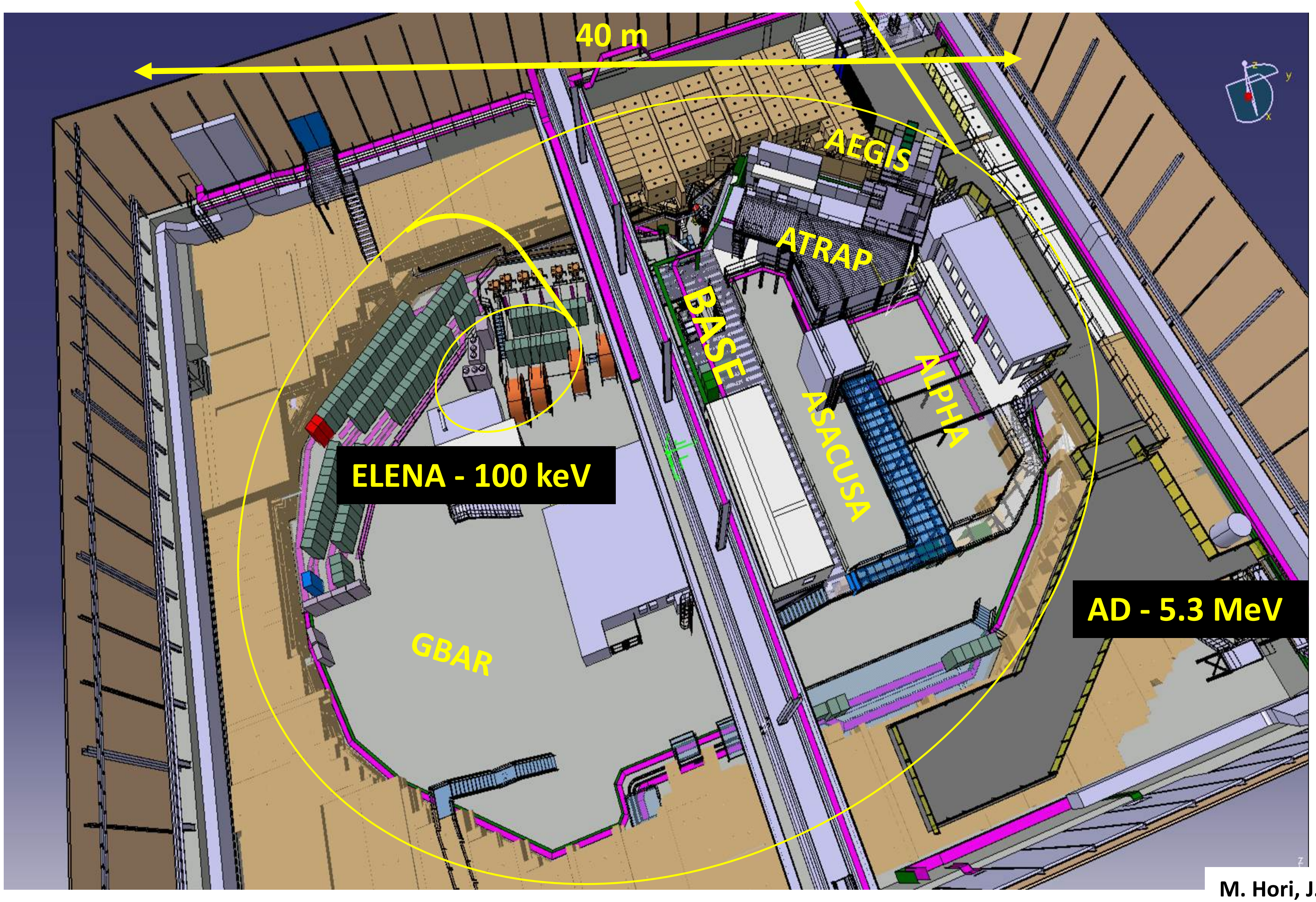








Physics in the AD/ELENA-facility



BASE, ATRAP,
Fundamental properties of the antiproton

ALPHA, ATRAP,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ASACUSA
Antiprotonic helium spectroscopy

ALPHA, AEgIS, GBAR
Test free fall/equivalence principle with antihydrogen

M. Hori, J. Walz, Prog. Part. Nucl. Phys. 72, 206-253 (2013).

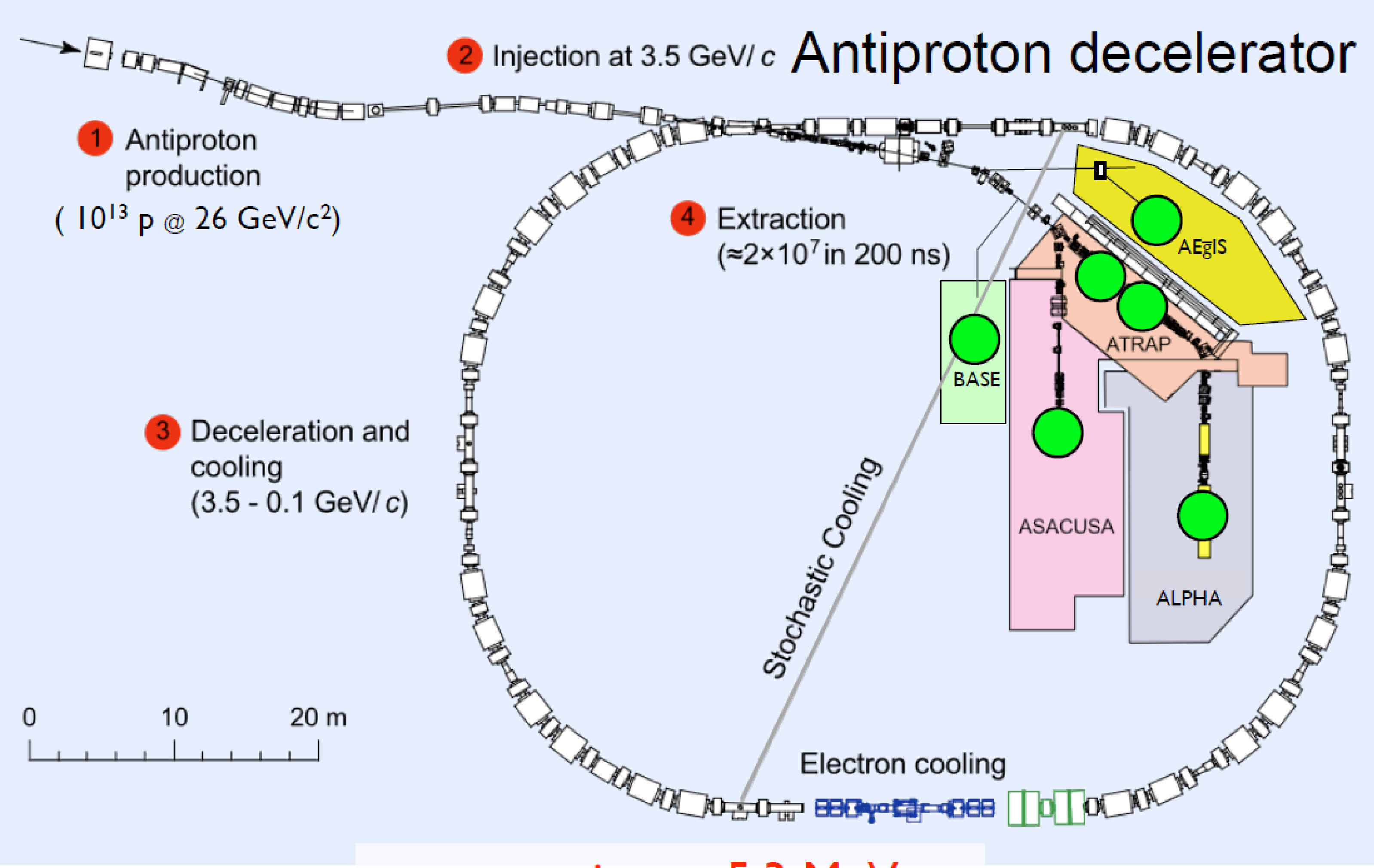
Why do we need antiparticles at rest?

- Precision experiments:
  "Never measure anything but frequency" – A. Schawlow

- Observation time $\leftrightarrow$ Fourier limit
  Confinement increases the observation time

- Systematic limits often scale with temperature
  - Laser spectroscopy: Doppler shift
  - Single (anti)particle experiments: Trap imperfections, relativistic shift
- Antihydrogen synthesis: Recombination cross-section $\propto T^{-x}, x > 0$

Antiproton decelerator in 2015



extraction at 5.3 MeV

figure from M. Doser

Proton Synchrotron beam on irdium target: Pair production of antiprotons

Focusing and separation of antiprotons

Antiproton decelerator:
Synchrotron for antiprotons

Decelerates from 3.6 GeV to 5.3 MeV by

1.) Rf-deceleration
2.) Stochastic cooling
3.) Electron cooling

Ejection to experiments:
30 million antiprotons in 200 ns
every 110 s

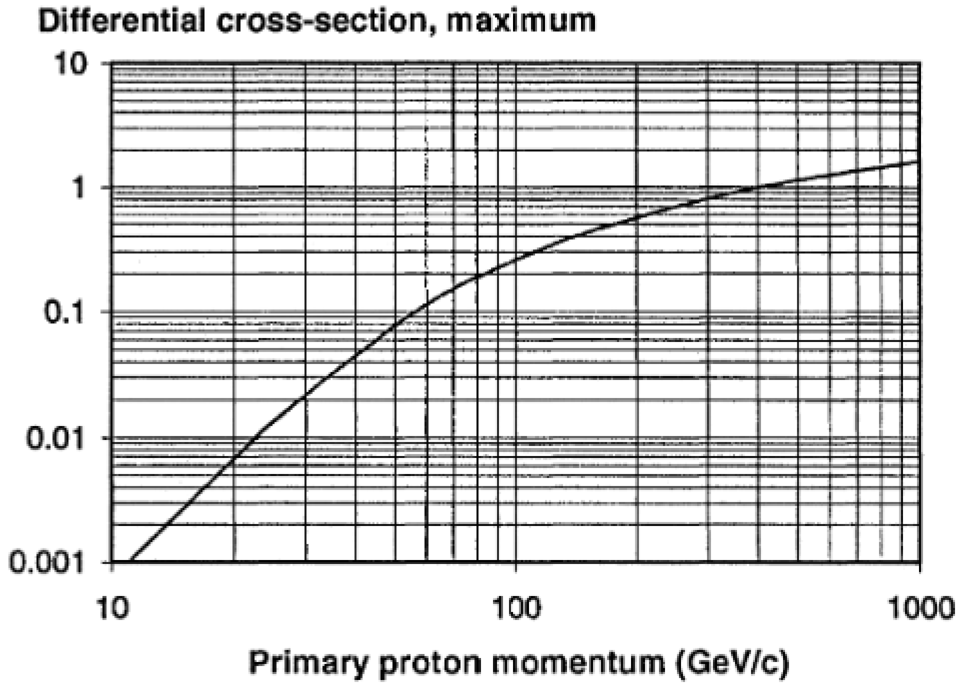
Production of Antiprotons

Pair creation in HEP reaction:

$$p + p + E_{kin} = p + \bar{p} + p + p$$

Fixed target threshold energy for antiproton production

$$E_{kin} = 5.63 \text{ GeV}$$

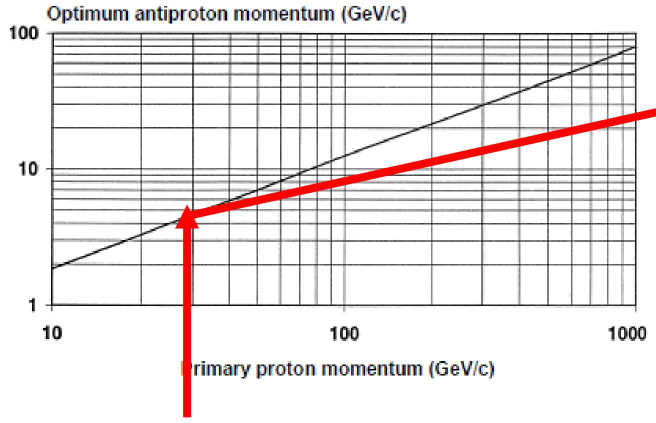


Higher energy gives higher yield, but the antiproton momentum (~center of mass momentum) increases!

D. Moehl, Hyp. Int. 109, 33 (1997).

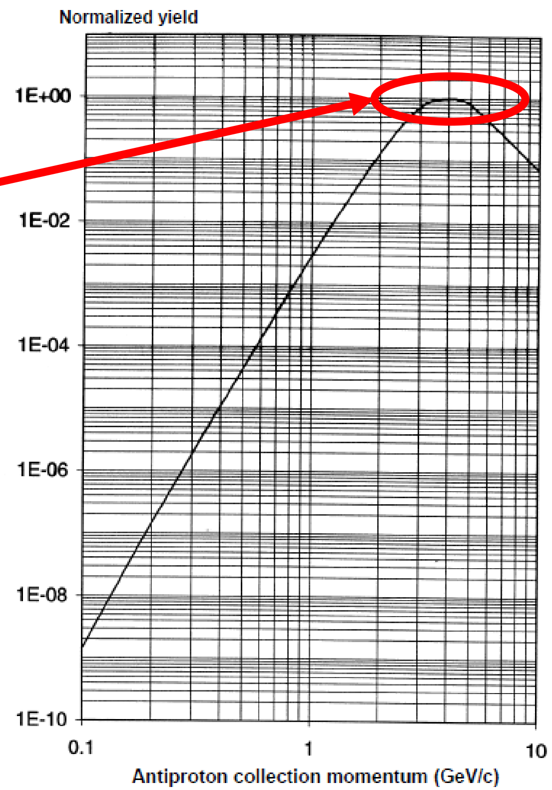
Design considerations

Efficiency: 1e-6



CERN Proton Synchrotron (27 GeV/c)

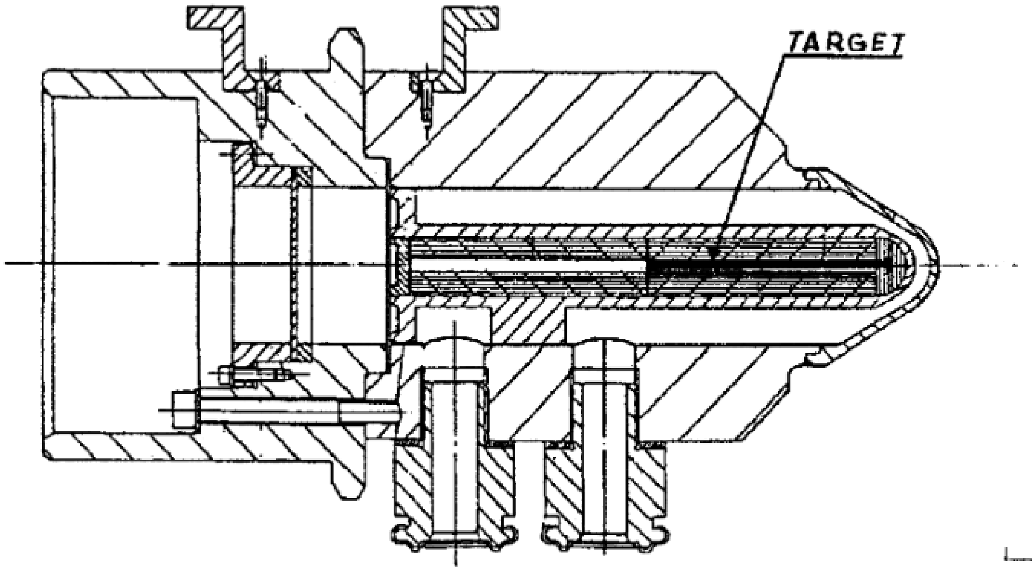
Collection at low energy not possible



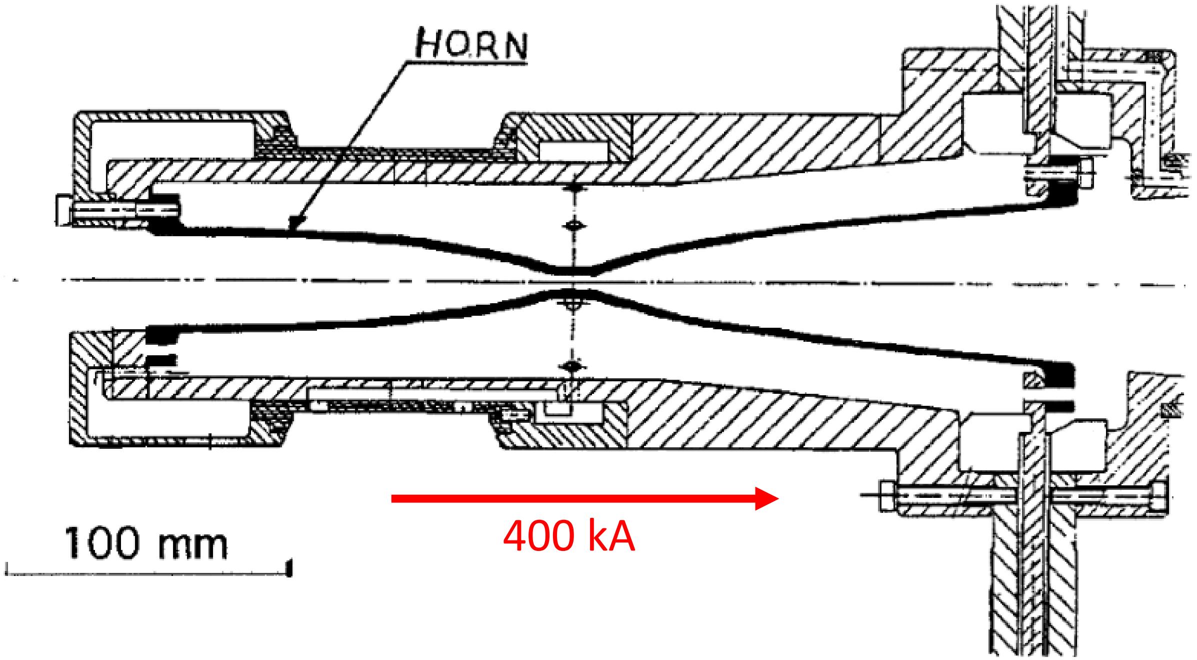
3.57 GeV/c

D. Moehl, Hyp. Int. 109, 33 (1997).

The antiproton production target



Iridium rod (L = 55 mm, d = 3 mm)



Azimuthal magnetic field to focus the antiprotons

Target: Highest density, high melting point, stability against thermal shock

Limit in production yield: target heating by the proton beam (T < 1800 K)

D. Möhl, Hyp. Int. 109, 33-41 (1997).

The challenge: Cooling by ~10 orders of magnitude

Antiproton production: ~ 3.7 GeV

AD final energy: ~ 5.3 MeV

Trap injection energy: < 5 keV

Present cooling limit: 0.5 meV

rf-deceleration

Stochastic Cooling

Electron Cooling

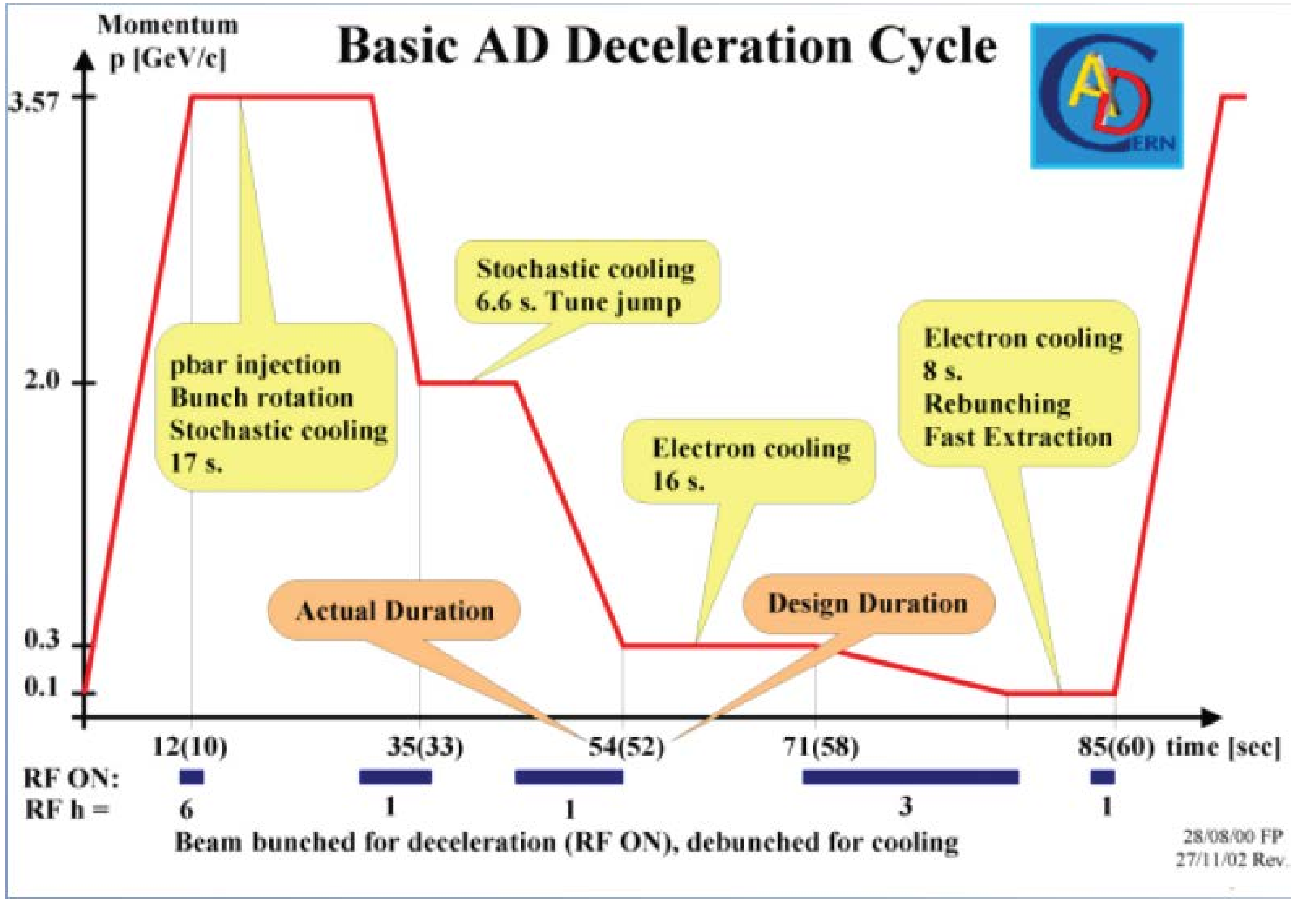
Degrader

Sympathetic cooling

Resistive cooling

Laser-cooled ions?

AD Cycle

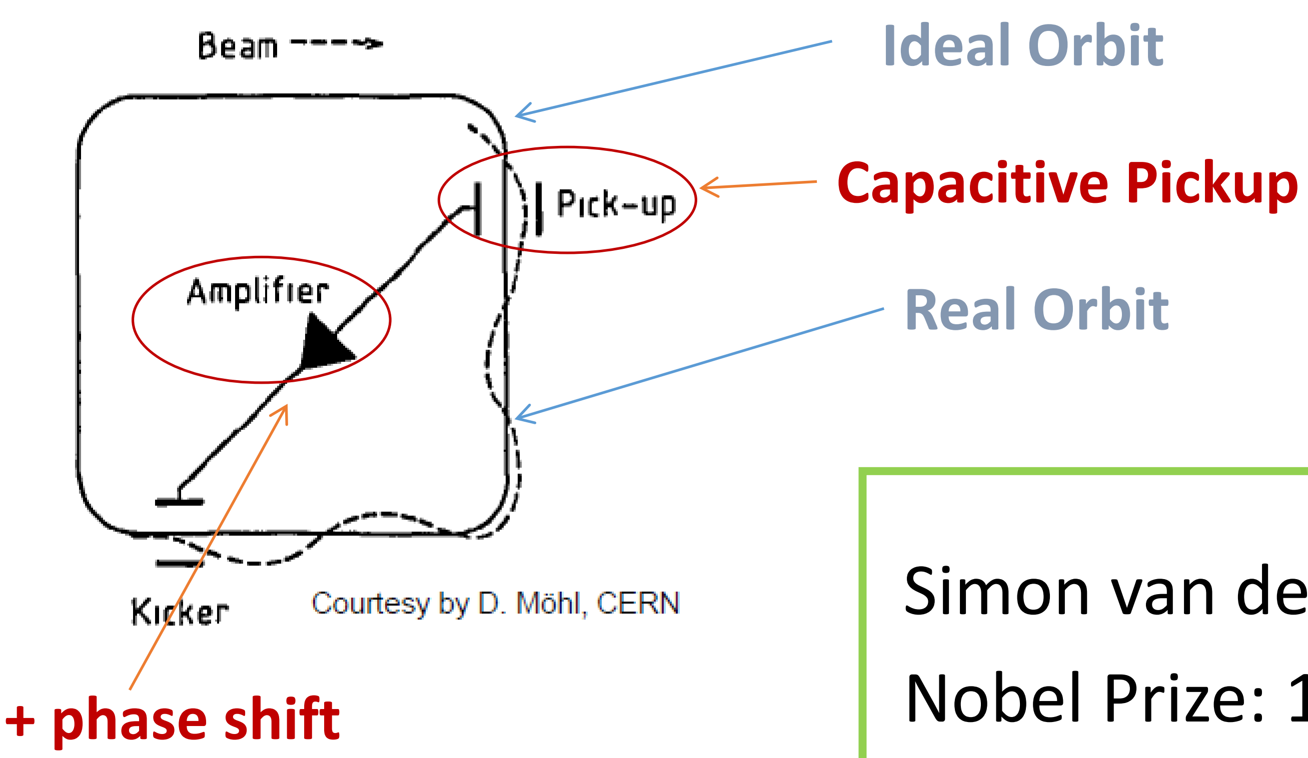


- Antiprotons injected into the AD: finite phase, energy, momentum, position spread.
- Leads to **betatron oscillation** and instabilities
- Liouville's theorem:
  the phase space is conserved!

- Adiabatic deceleration further increases the transverse emittance
- Cooling mechanisms are needed!

Stochastic Cooling

Reduce betatron oscillations by signal pickup and active electronic feedback

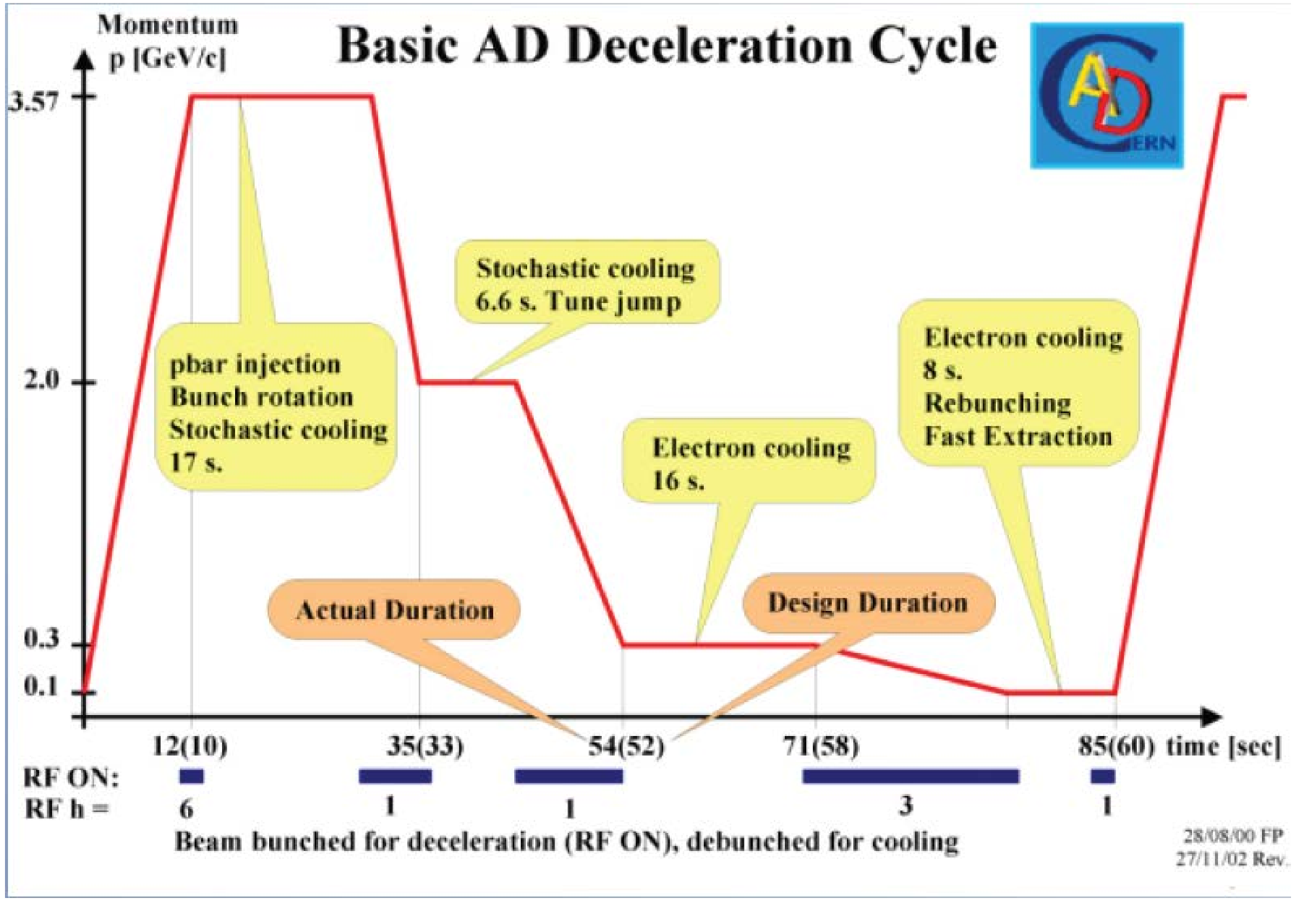


Simon van der Meer (1925 – 2011)

Nobel Prize: 1984

Technical developments applied to Sp$\bar{p}$S -> discovery of W, Z bosons

AD Cycle



Momentum p [GeV/c]
Basic AD Deceleration Cycle
3.57
2.0
0.3
0.1
Stochastic cooling 6.6 s. Tune jump
pbar injection Bunch rotation Stochastic cooling 17 s.
Electron cooling 8 s. Rebunching Fast Extraction
Electron cooling 16 s.
Actual Duration
Design Duration
12(10)
35(33)
54(52)
71(58)
85(60) time [sec]
RF ON:
RF h =
6
1
1
3
1
Beam bunched for deceleration (RF ON), debunched for cooling
28/08/00 FP
27/11/02 Rev.

Electron Cooling

Electron in a strong magnetic field: Cyclotron Motion

Permanently accelerated charge

-> Maxwell equations -> electron irradiated photons

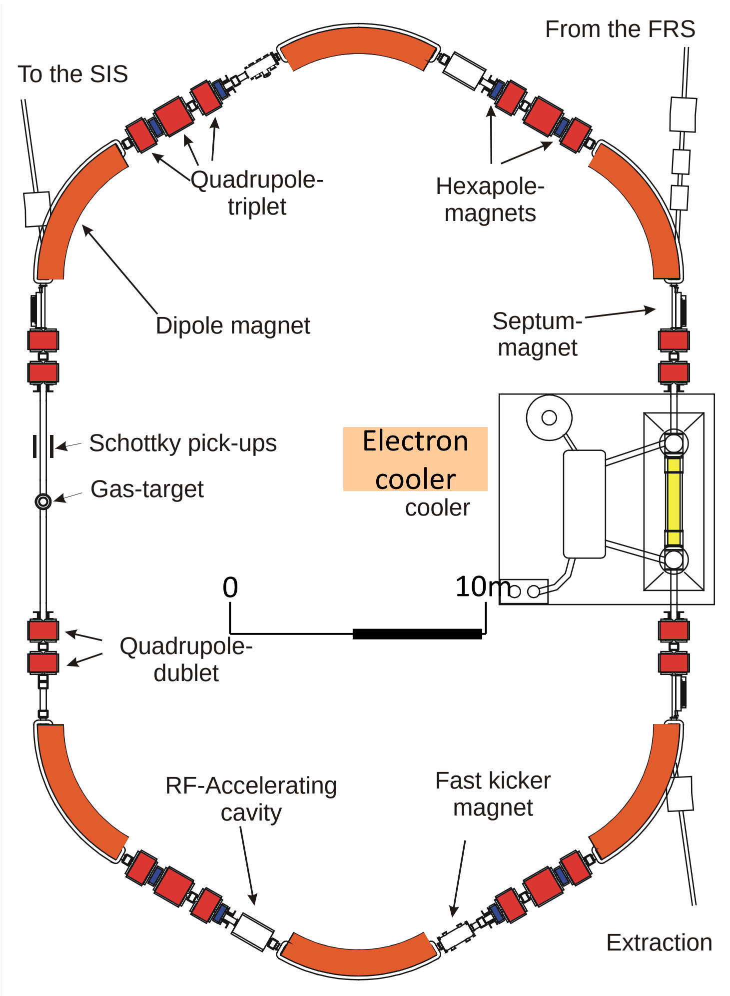
Typical magnetic fields (T)

COOLDOWN to ambient temperatures within 0.1s

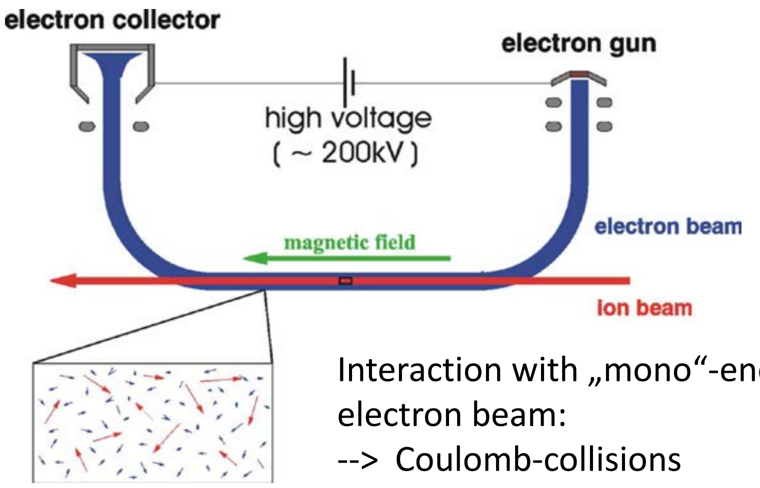
$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{e^2 a^2}{6\pi\epsilon_0 c^3}$$

$$\tau = \frac{3\pi\epsilon_0 m^3 c^3}{e^4}\frac{1}{B^2}$$

Electron cooling



momentum exchange by Coulomb collisions

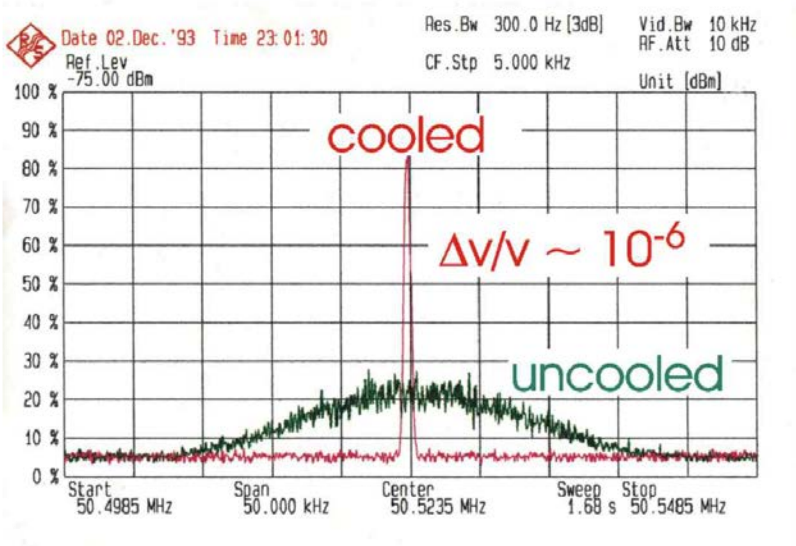


Interaction with „mono“-energetic electron beam:

--> Coulomb-collisions

--> Temp. compensation: $T_{ion} = T_e$

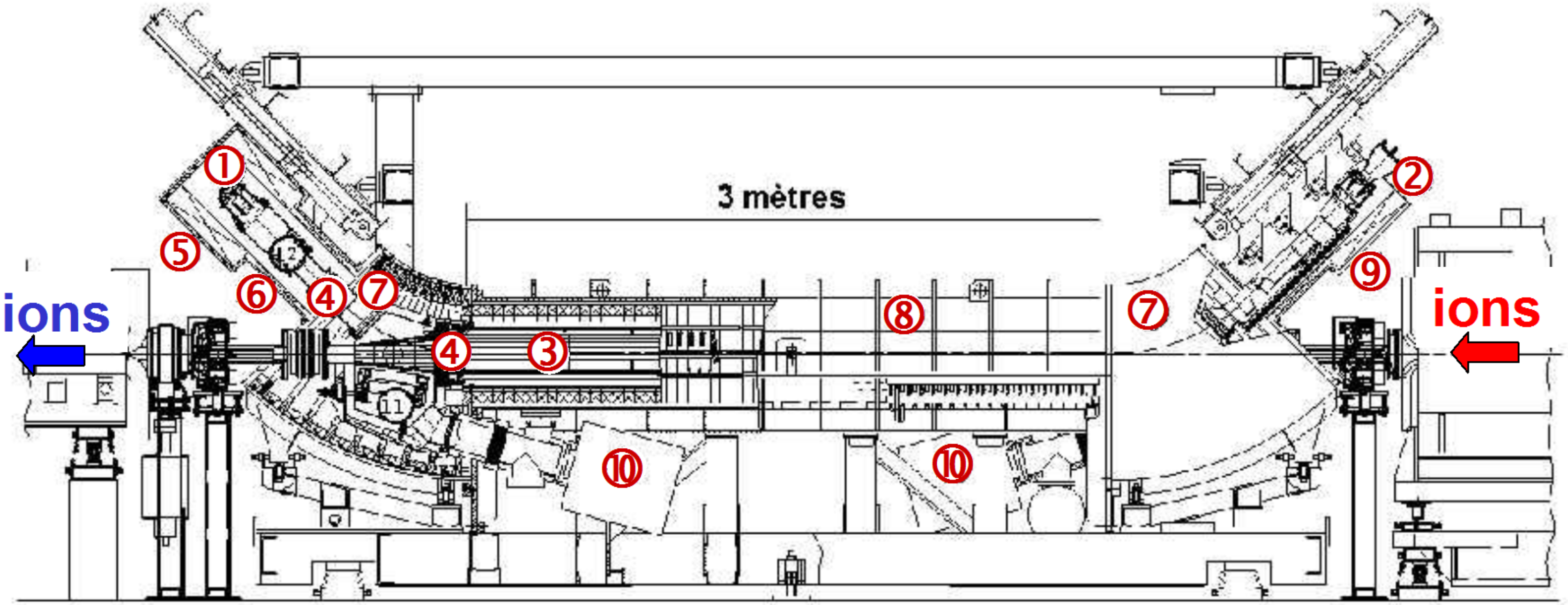
--> Cooling: $\delta v_{ion} = \delta v_e * \text{sqrt}(m_e/m_{ion})$



Note: Cooling limit

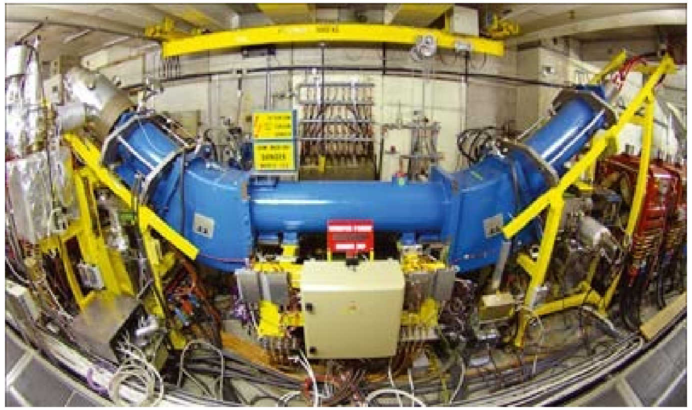
The antiprotons are only cooled on a small fraction of their flight path. On the remaining orbit heating, which is at low energies dominated by space-charge driven expansion of the antiproton bunch, counteracts the cooling process.

Electron cooling



① electron gun
② electron collector
③ central drift tube
④ clearing electrodes
⑤ gun solenoid
⑥ expansion solenoid
⑦ toroid
⑧ cooling solenoid
⑨ collector solenoid
⑩ sputter ion pumps

Long cooling times (order of s) needed!



AD electron cooler, photo: CERN Courier

Ions interact 10^6 1/s with a collinear beam of cold electrons.

Properties of the cold ions: momentum spread $\Delta p/p = 10^{-4} - 10^{-5}$
diameter $d = 2$ mm

AD Performance

QTY	#
Start Energy	3.5 GeV
Stop Energy	5.3 MeV
Efficiency	Typical 80%
Cycle length	120s
Bunch length	150ns
Particle per bunch	about 30.000.000
Catching Efficiency	< 1%

Some comments:

Slow AD cycles – one information in 2 minutes debugging is time consuming!

In one week, 3 experiments run in sequence for 8 hours shifts

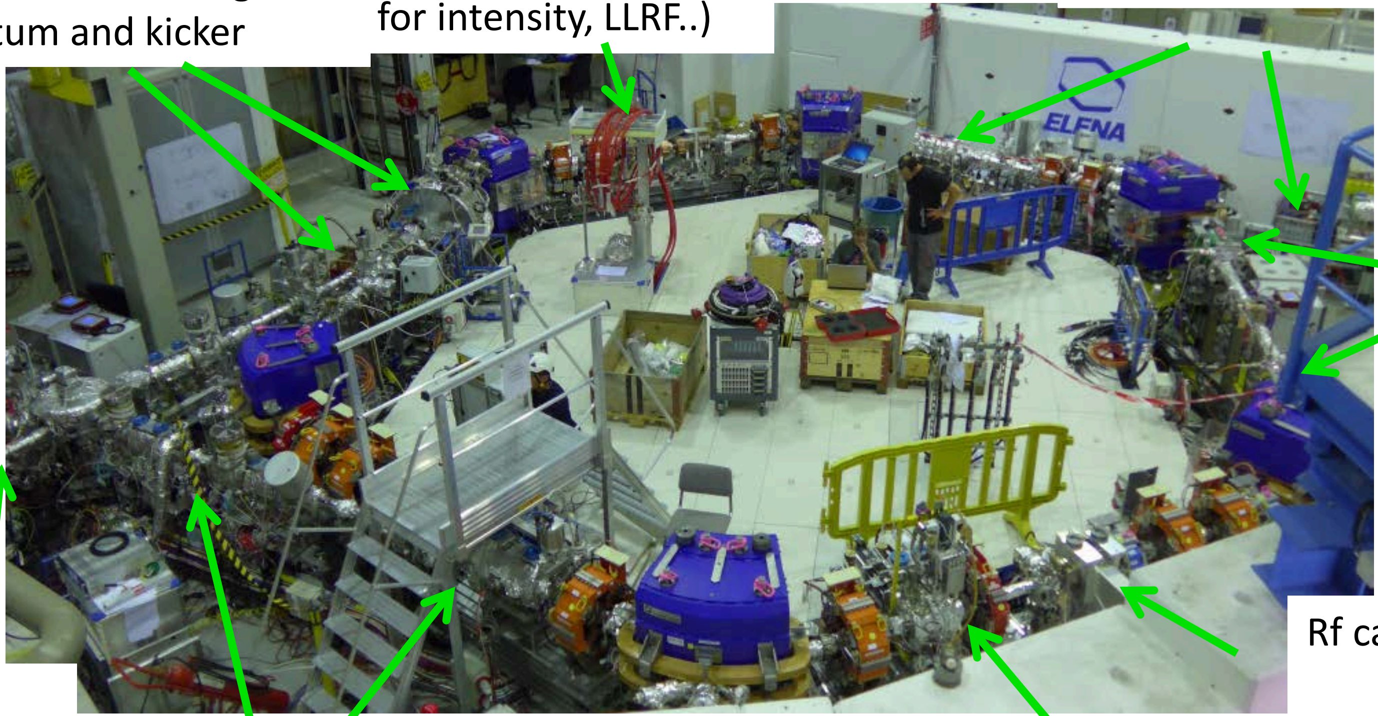
Catching efficiency of 5.3 MeV antiprotons is low!

ELENA Overview and Layout

Injection with magnetic septum and kicker

High sensitivity magnetic Pick-up (Schottky diagnostics for intensity, LLRF..)

Extraction towards new experimental zone



Compensation solenoids for (not yet Installed) cooler

Rf cavities

Line From AD

Extraction towards existing experiments

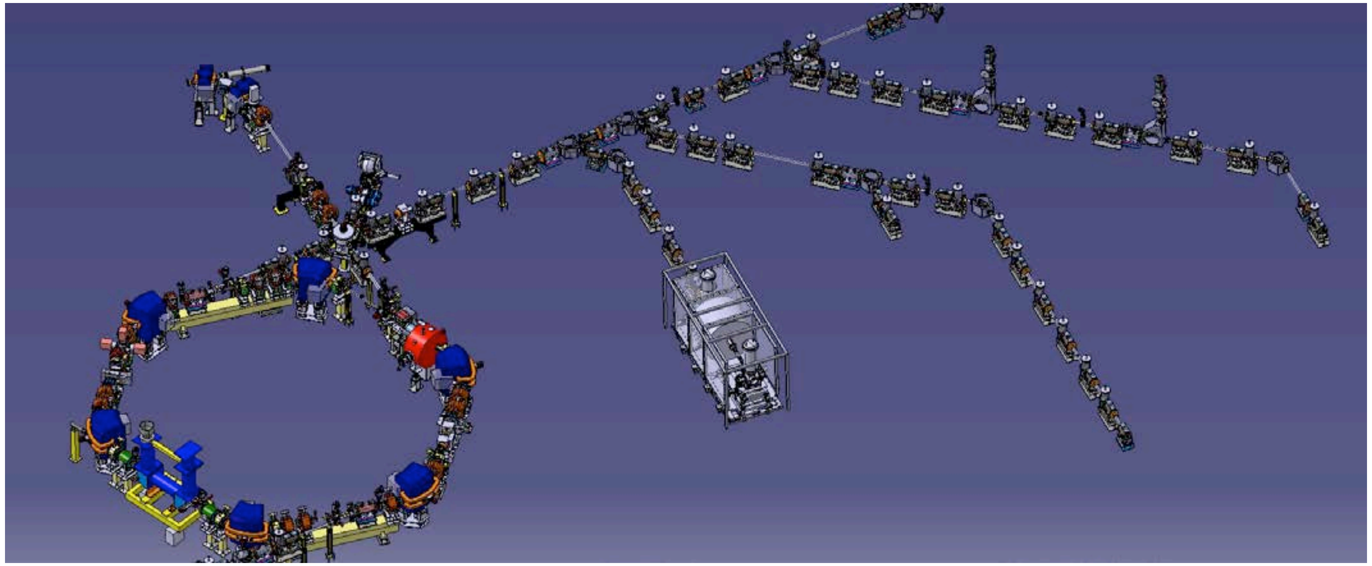
Scraper to measure emittance

- Deceleration of antiprotons from 5.3 MeV to 100 keV to improve efficiency of experiments
- Circumference 30.4 m (1/6 the size of the AD), magnetic ring and electrostatic extraction lines
- Challenges related to low energy as field quality of magnets operated with very low fields

Courtesy of C. Carli

W. Oelert, arXiv: 1501.05728 (2015).

ELENA Upgrade – 100 keV antiprotons



Separation of the AD bunch into 4 bunches (space charge limit)

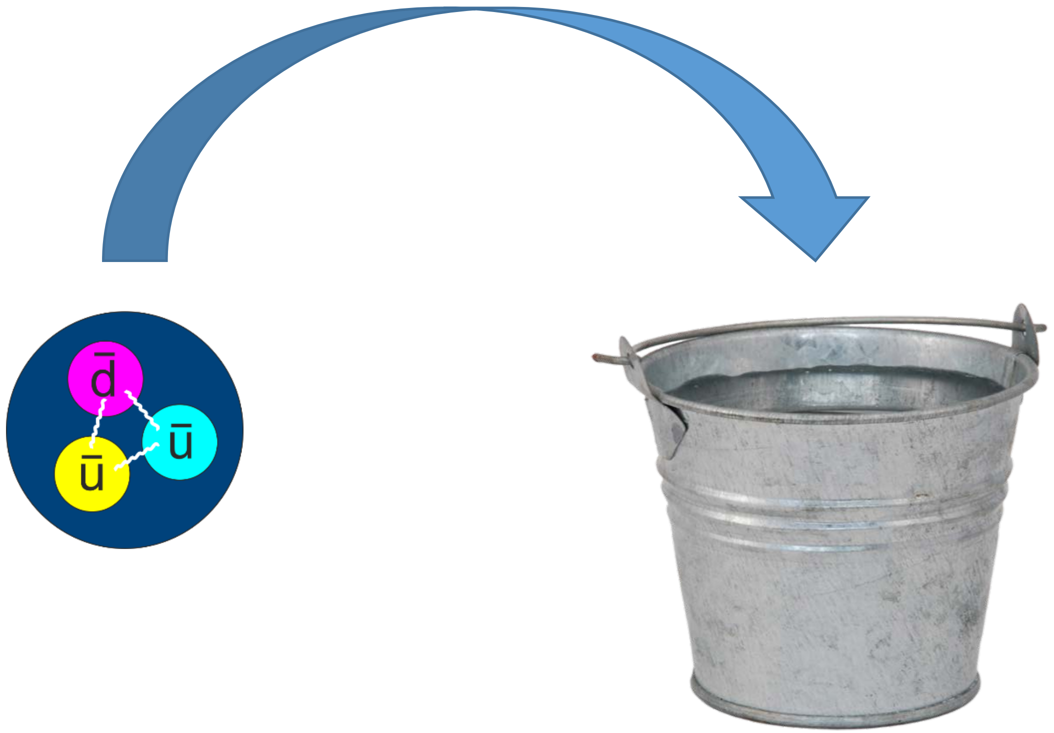
Supply of 4 experiments simultaneously
24/7 beam for four experiments

Supply of the GBAR experiment from next year

All other experiments from 2021

W. Oelert, arXiv: 1501.05728 (2015).

Next step – collect all the antiprotons!



Important Question: What do we do with all the antimatter?

Of course…


ANGELS & DEMONS
天使と悪魔
ANGELS & DEMONS


EXTREME PHYSIK
In Dan Browns Bestseller »Illuminati« planen Verschwörer, den Vatikan auszulöschen.
Dass sie dafür Antimaterie verwenden wollen, mag als reine Sciencefiction erscheinen.
Aber der Eindruck täuscht: Die Forscher entdecken immer neue Einsatzmöglich-
»WIR JAGEN DEN VATIKAN
IN DIE LUFT. MIT

How much antimatter do we get?

30 million antiprotons in 2 minutes

8×10^{12} antiproton per year

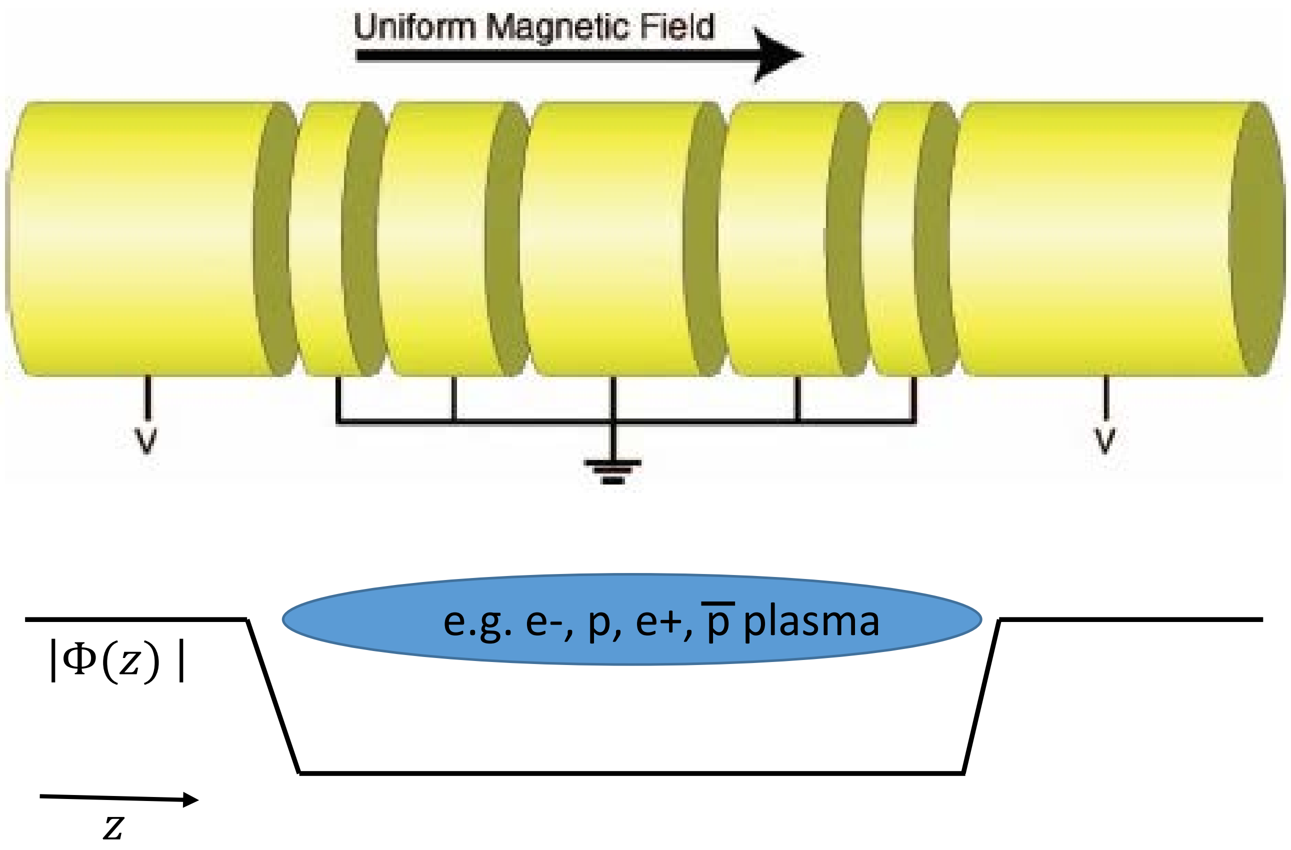
$E_{annihilation} = 2mc^2 = 2.4$ kJ/year

Your antimatter bomb can…

…prepare one expresso about every leap year

25 ml of water / 88 degrees

How to store (anti)particles?



A plasma of charged (anti-)particles can be confined in a Penning-Malmberg trap

Radial confinement by magnetic field

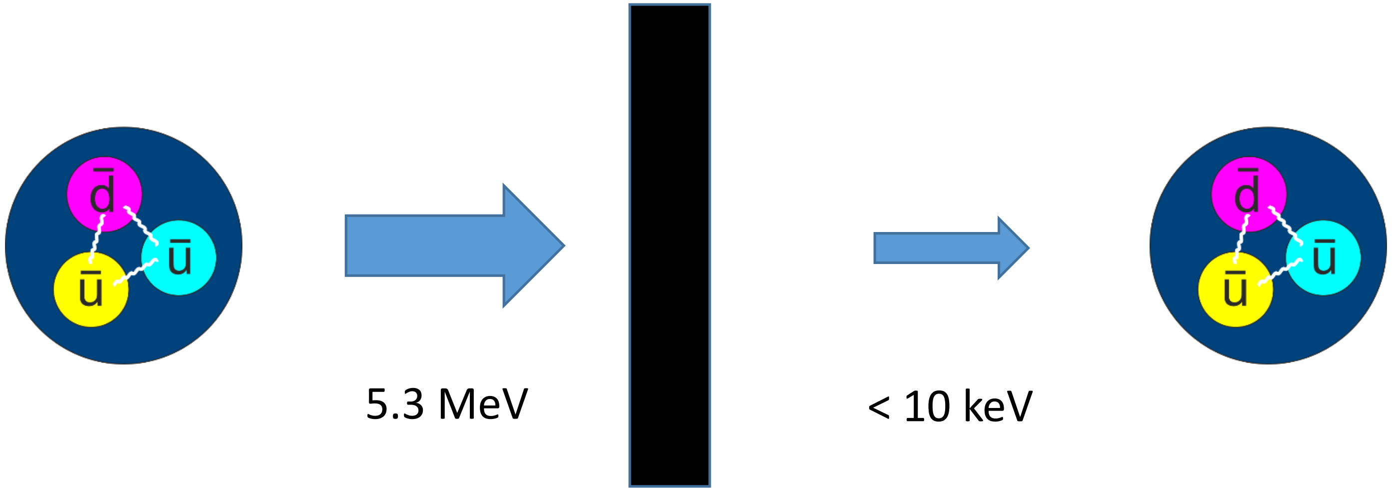
Electrostatic confinement by axial electric field

Extremely good vacuum ($p \ll 10^{-10}$ mbar)

Antiprotons with 5.3 MeV are still to fast to be confined by the electric potential (< 10 kV)

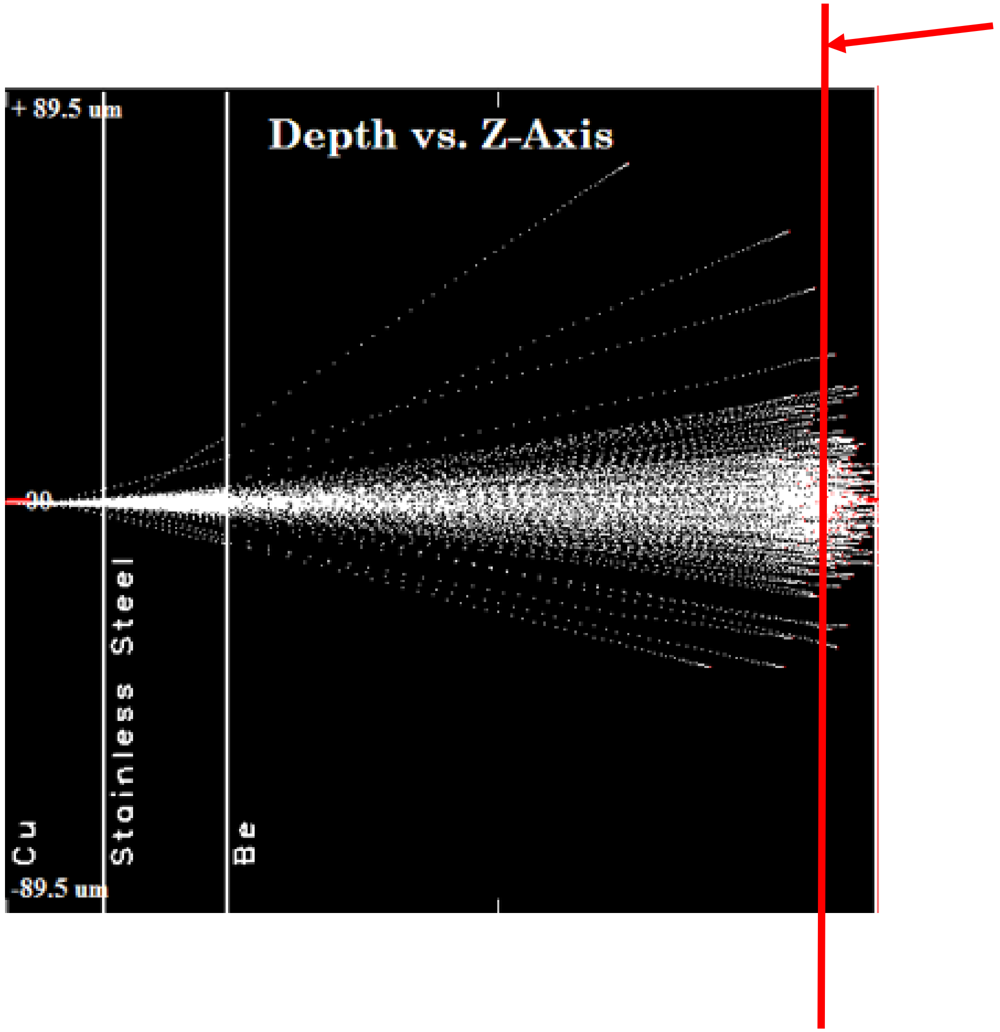
(Figure from Charlton et. al, "Antihydrogen for precision tests in Physics" 2008.)

Deceleration by “degrader foils”



How thick do you make the foil to maximize the antiproton yield?

Antiproton scattering



Best choice:

Exit surface is placed in the plane of the mean stopping range

Concerns:

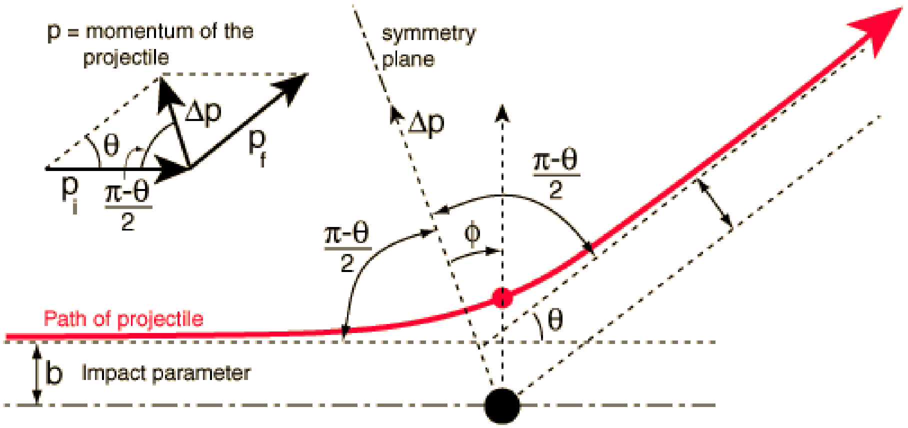
50 % losses by annihilation in the degrader

Broad energy distribution

Beam divergence increases

Bethe-Bloch Formula

Energy loss due to scattering of the projectile with electrons in the material



$$-\frac{dE}{dx} = \frac{\kappa}{\beta^2} n_e Z_1^2 \cdot L(\beta)$$

$$\kappa = \frac{e^4 c^2}{4\pi \varepsilon_0^2 m_e}$$ constant from scattering theory

$L(\beta)$ stopping number

Electron treated as **"quasi-free"** particle **at rest**

Projectile energy >> electron binding energy
Projectile velocity >> electron velocity

J.F. Ziegler, J. Appl. Phys. **85**, 1249-1272 (1999). *(Author of SRIM)*

The zero-order term

$$L_0(\beta) = Ln\left[\frac{2m_e c^2}{\langle I \rangle}\frac{\beta^2}{(1-\beta^2)}\right] - \beta^2 - \frac{C(\beta)}{Z_2} - \frac{\delta(\beta)}{2}$$

Empirical or model based data is required for:

- The average excitation/ionization potential: $\langle I \rangle$
  Correction for quantized energy of the electrons
- Shell correction $C(\beta)/Z_2$ to account for electron velocity
- Density corrections accounting for polarization of the medium $\delta(\beta)/2$

J.F. Ziegler, J. Appl. Phys. **85**, 1249-1272 (1999). *(Author of SRIM)*

The stopping number

The stopping power is usually expanded in a semi-empirical approach to include additional corrections compared to pure Rutherford scattering.

$$L(\beta) = L_0 + Z_1 L_1 + Z_1^2 L_2 + \dots$$

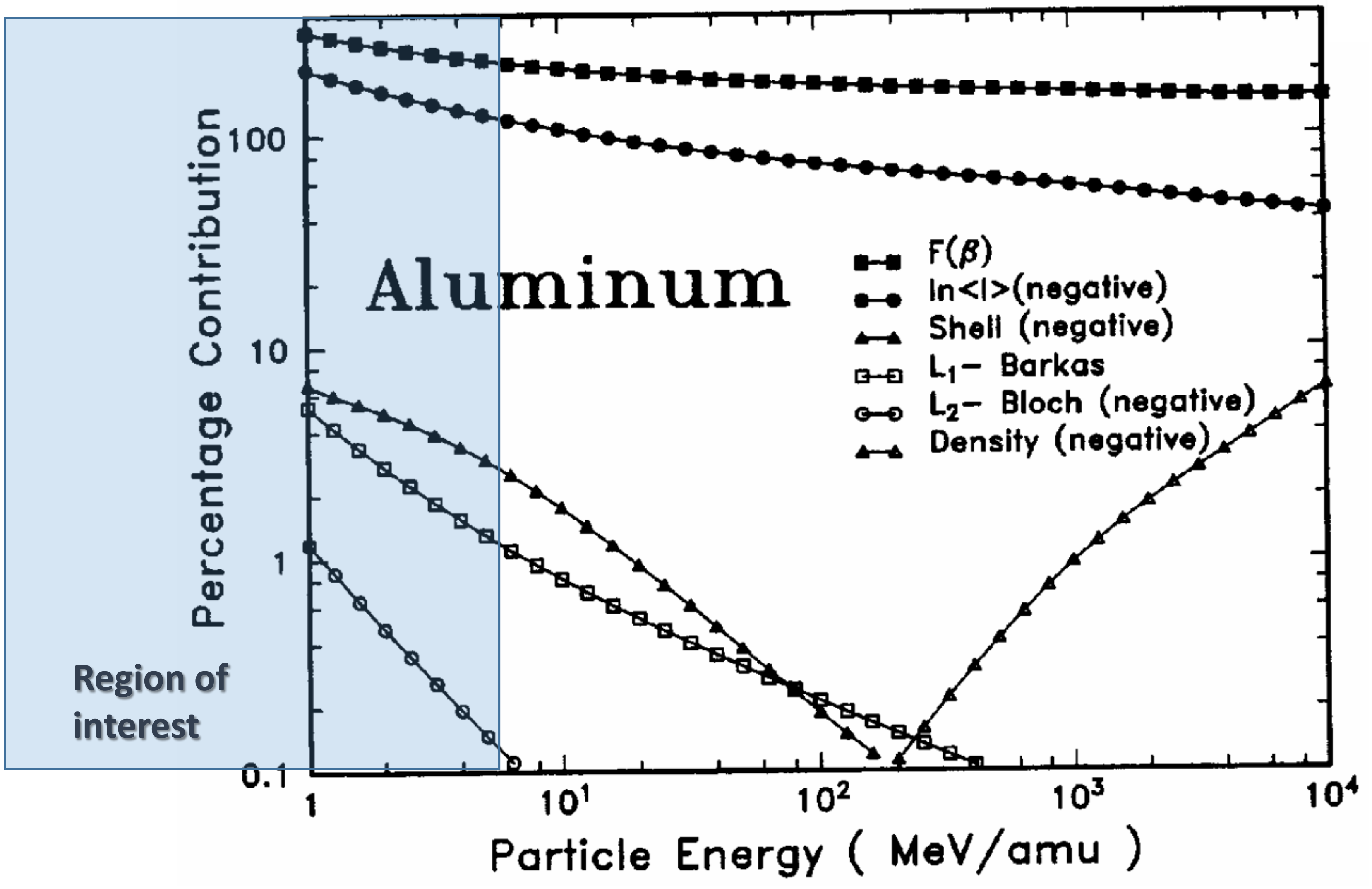
The zero-order term is the scattering term in the Bethe-Bloch formula

The **first-order** term is the Barkas term accounts for the difference in **polarization** of the medium depending on the projectile’s charge.
Difference in stopping power for protons and antiprotons!

The **second-order** term is the Bloch term, which accounts for e.g. **three-particle interactions**

J.F. Ziegler, J. Appl. Phys. **85**, 1249-1272 (1999). *(Author of SRIM)*

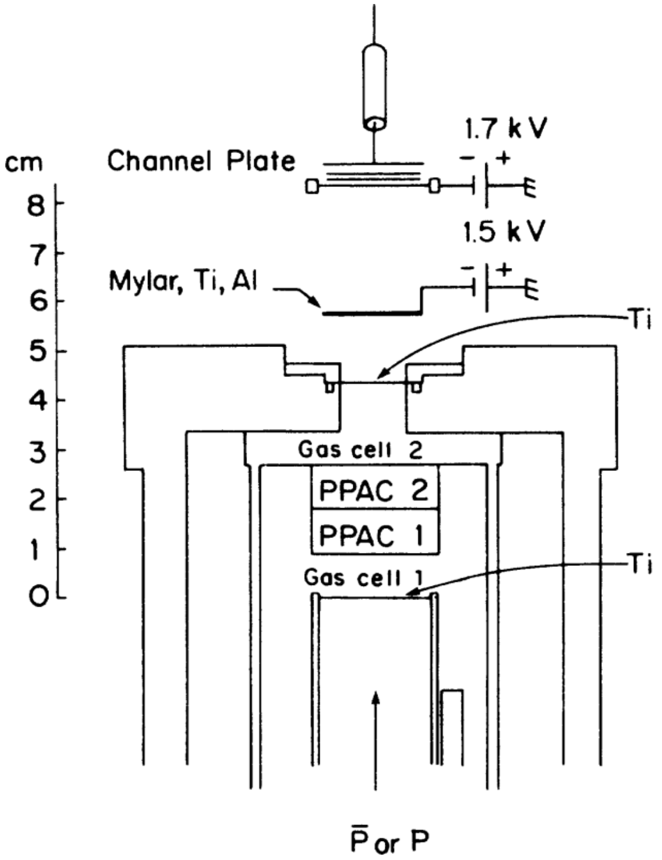
Contributions to the energy loss

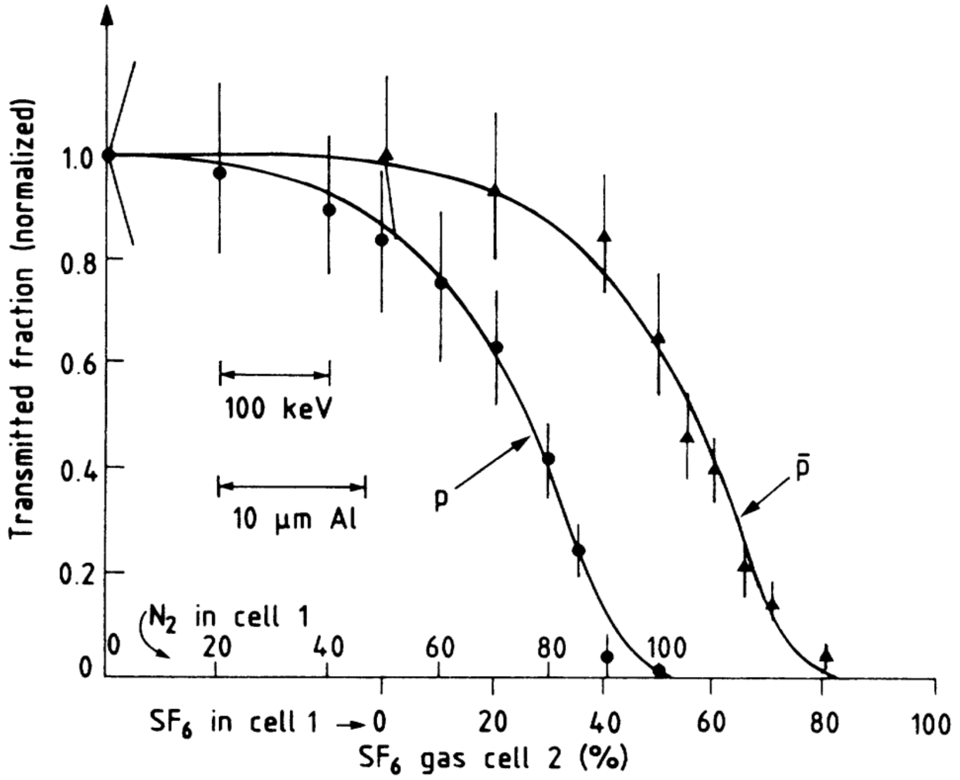


J.F. Ziegler, J. Appl. Phys. **85**, 1249-1272 (1999). *(Author of SRIM)*

Experimental solution #1

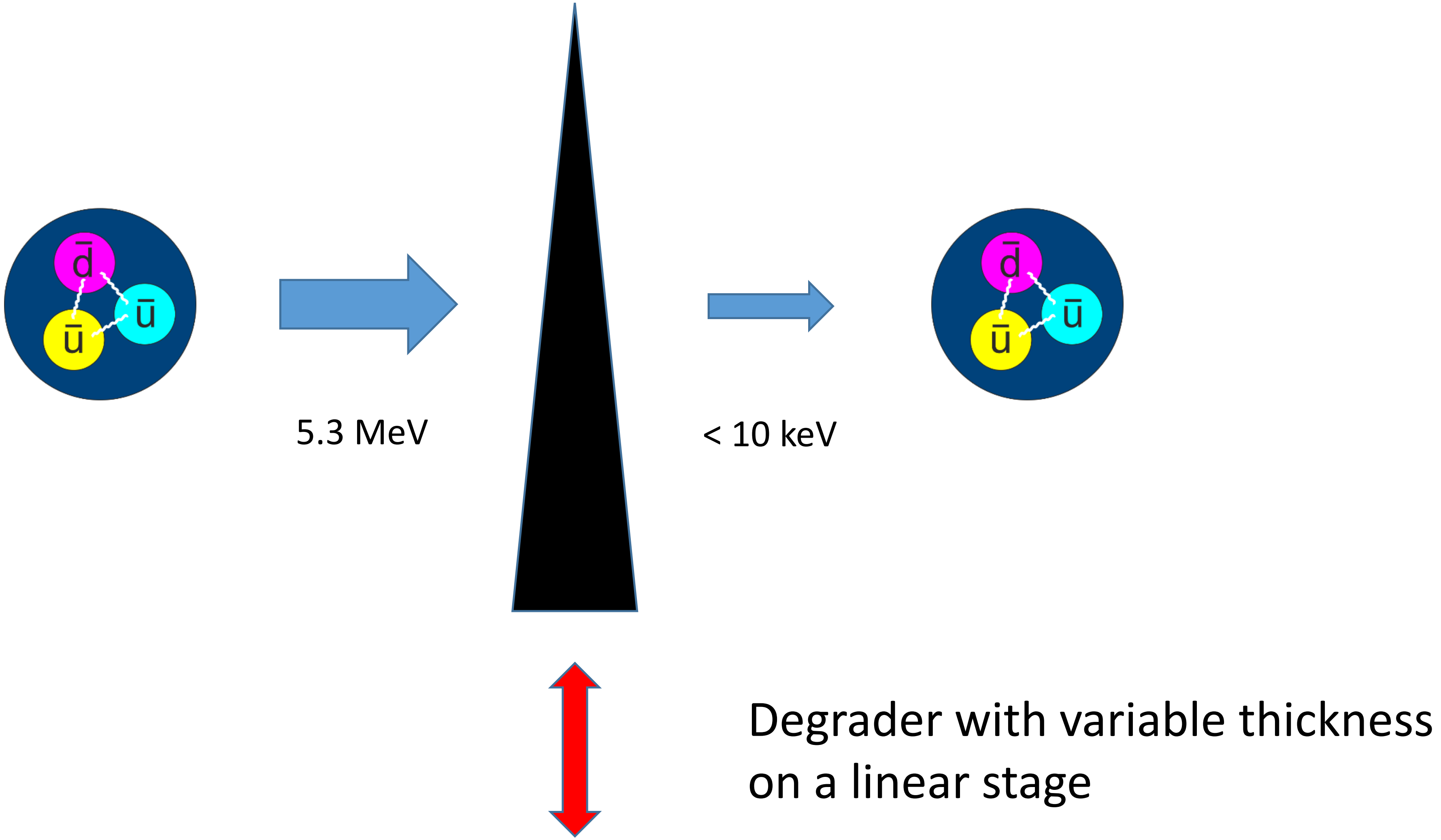
- Modulation of stopping power by pressure changes in gas cells





G. Gabrielse et al., Phys. Rev. A 40, 481 (1989).

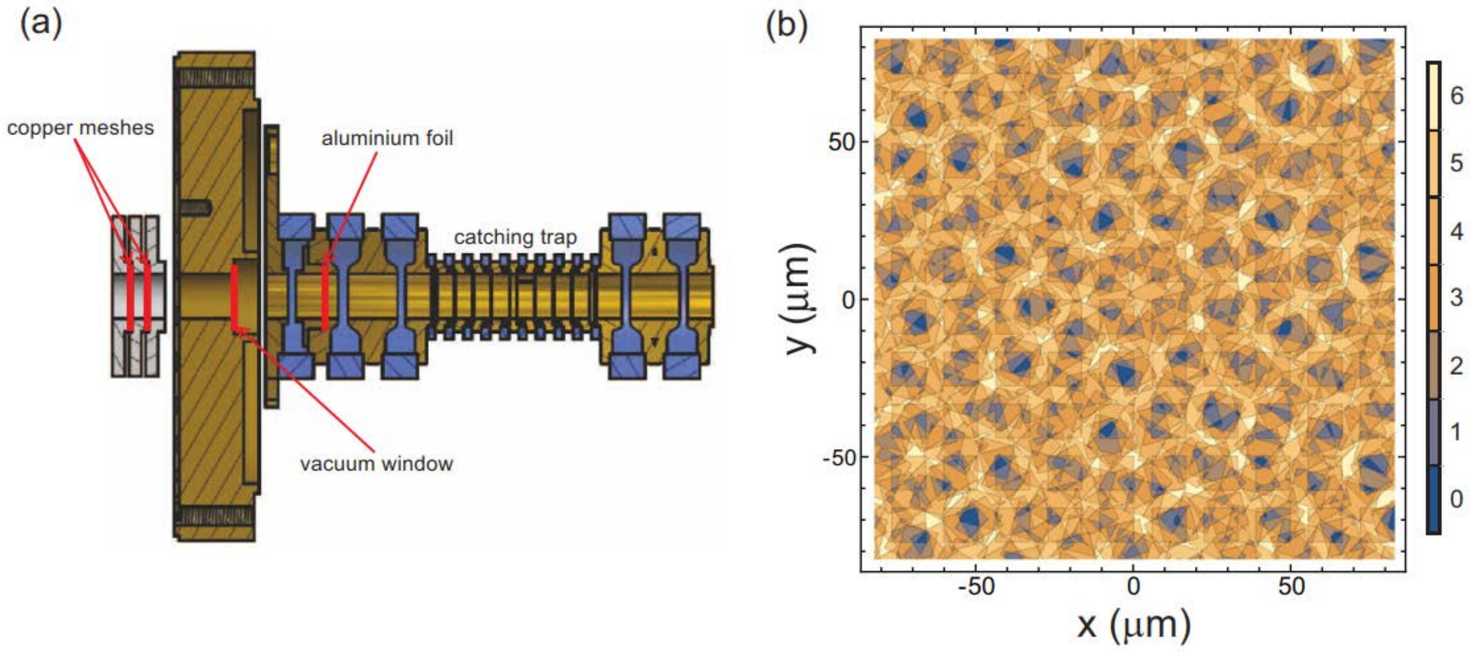
Experimental solution #2



Experimental solution #3

- A “mesh degrader”

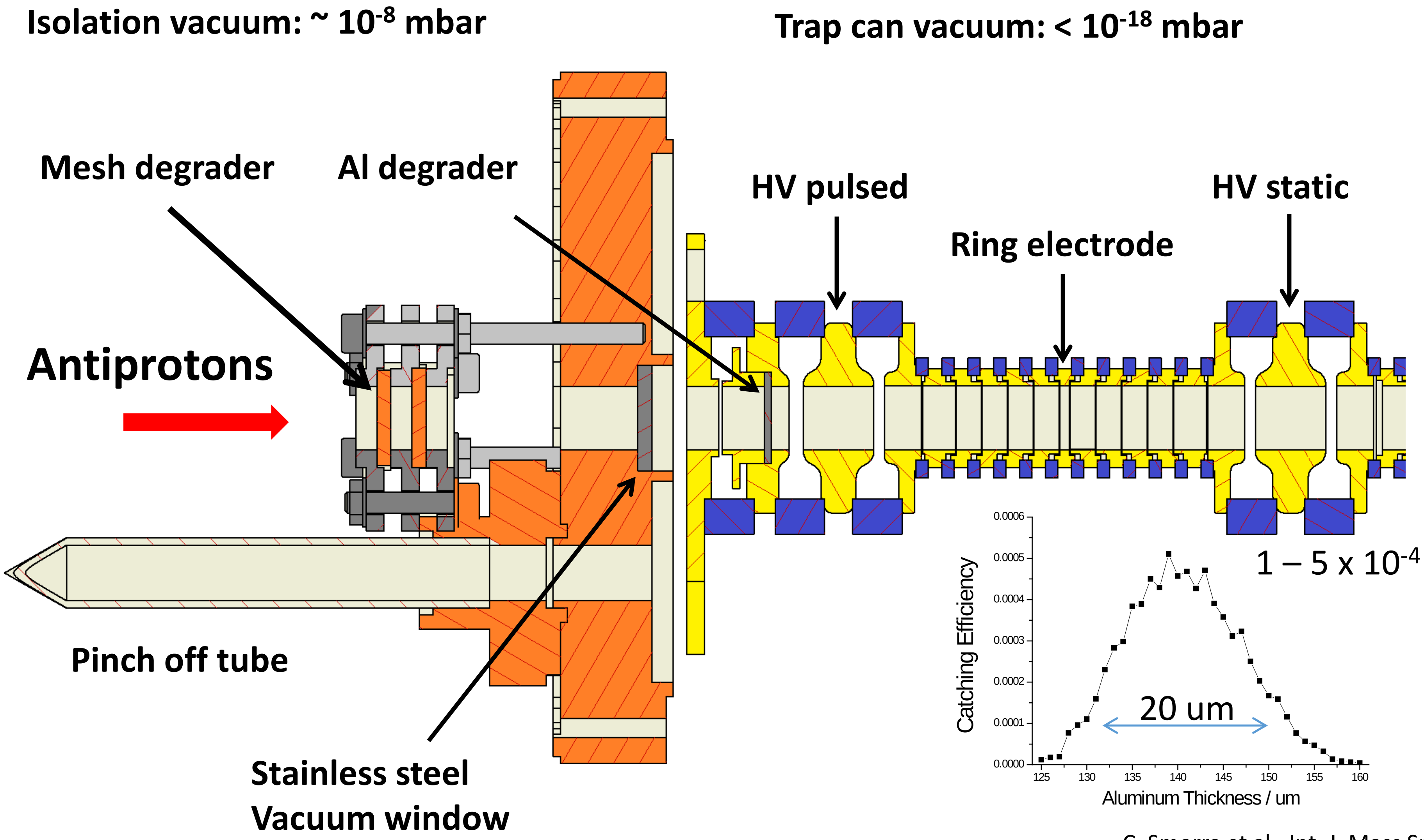
- Stack of thin meshes tilted against each other



- generates a “quasi-random” pattern with a structure small compared to the beam diameter

C. Smorra et al., Eur. Phys. J ST 224, 3055-3108 (2015).

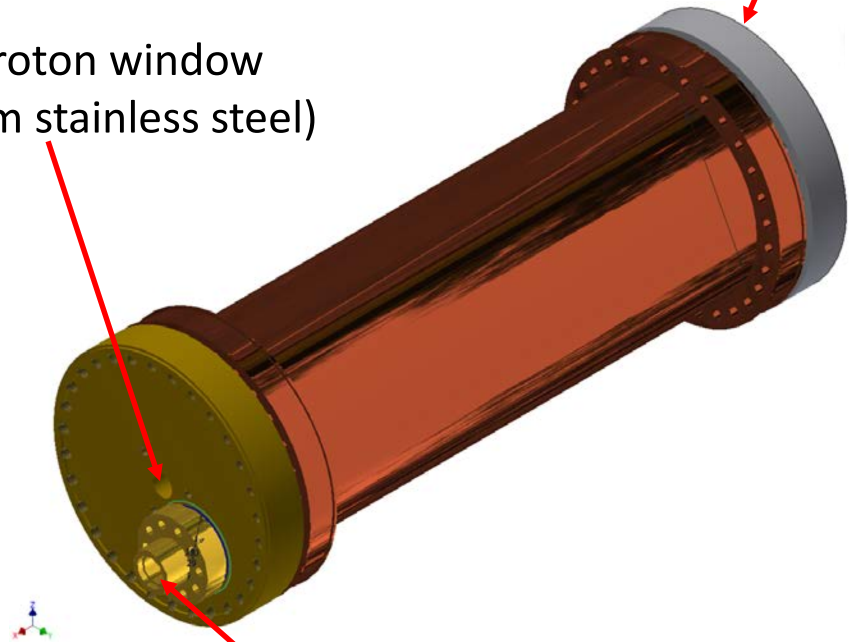
An antiproton catching trap



C. Smorra et al., Int. J. Mass Spectr. 389, 10 (2015).
S. Sellner et al., New J. Phys. 19, 083023 (2017).

How to get vacuum $p < 10^{-17}$ mbar?

- Pinch-off technique
  - Pump the trap chamber to $p < 10^{-6}$ mbar
  - Hermetically seal the vacuum chamber by "pinch off" of the pump connection
- Cool down to 4 K
  - No hydrogen diffusion in the walls
  - Freeze out of all gases except helium
  - Even helium attaches in a monolayer to surfaces by van-der-Waals force (T < 20 K)
- Pressure limits set by antiproton annihilation rates to $p \sim 10^{-18}$ mbar



How it looks in practice?

Indium wire as gaskets

Pinch off flange is exchangeable

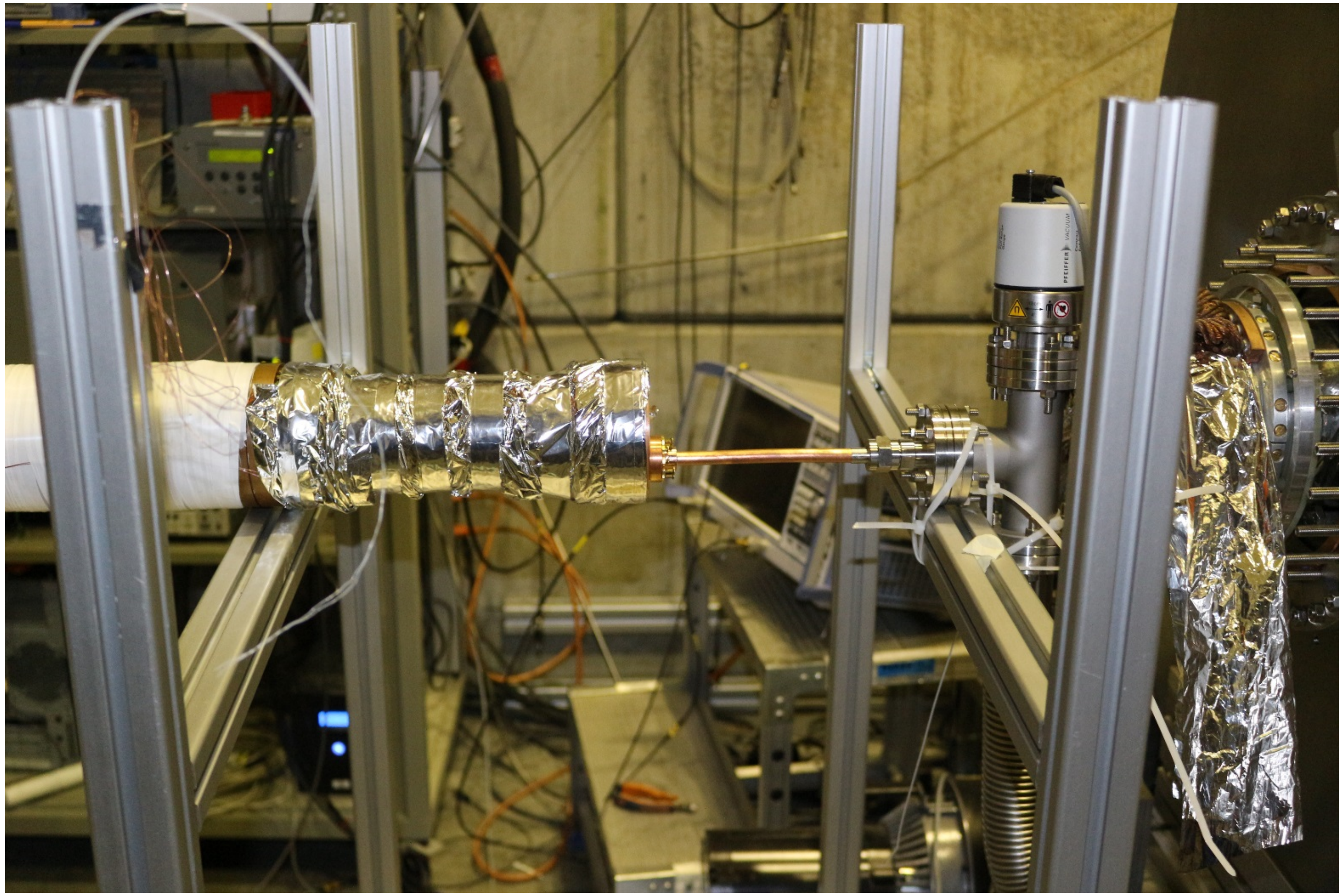
Tube is hard-soldered into the flange

3 days pumping

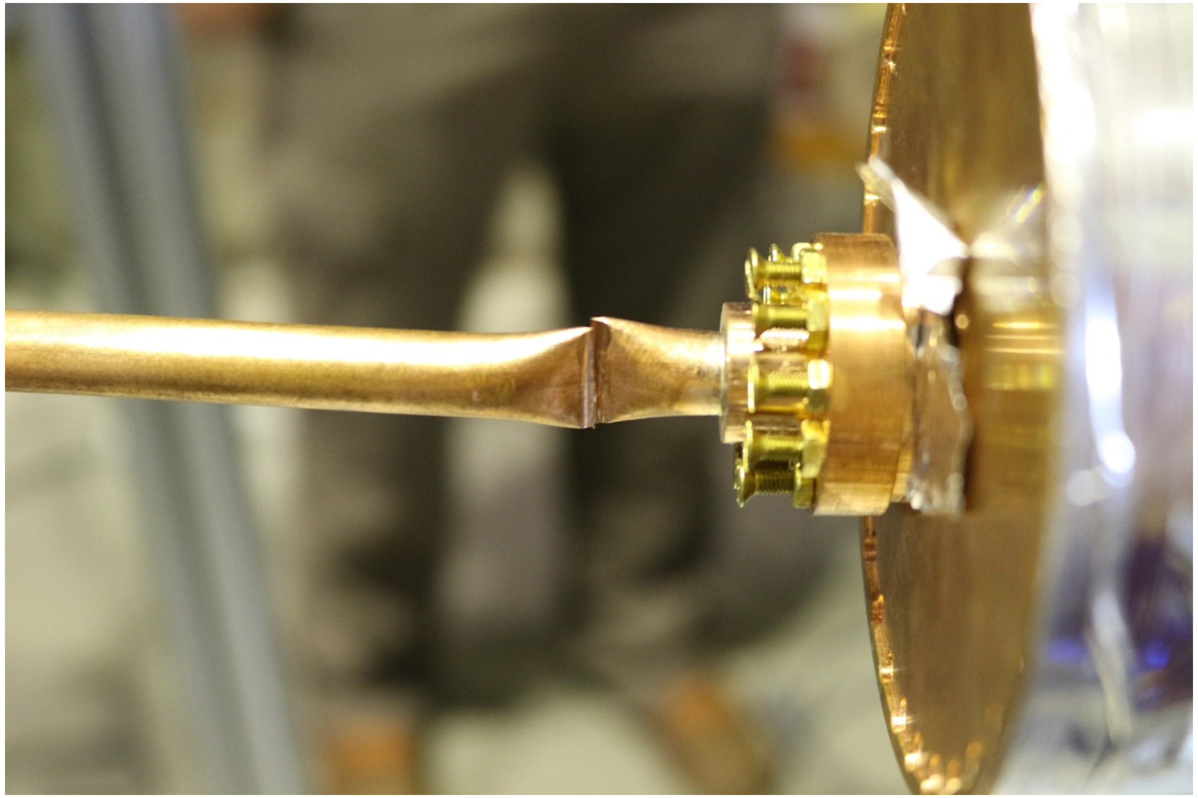
pinch-off

experiment installation (1 day)

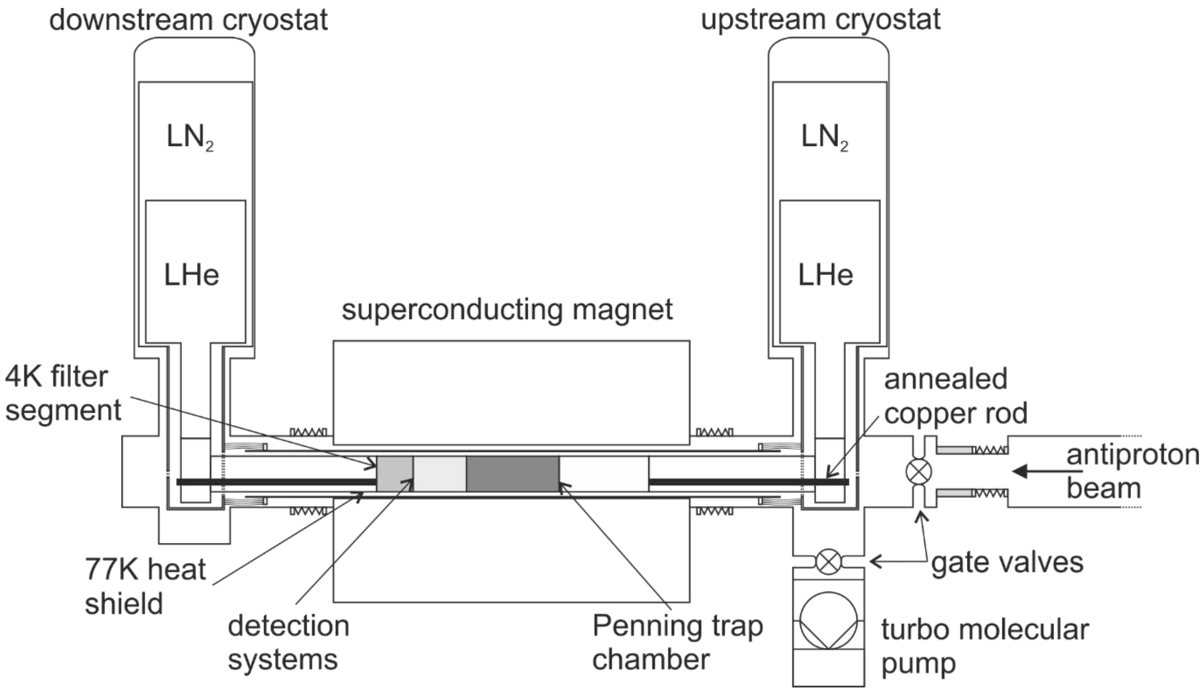
Cooling to 4.2 K – 24 h

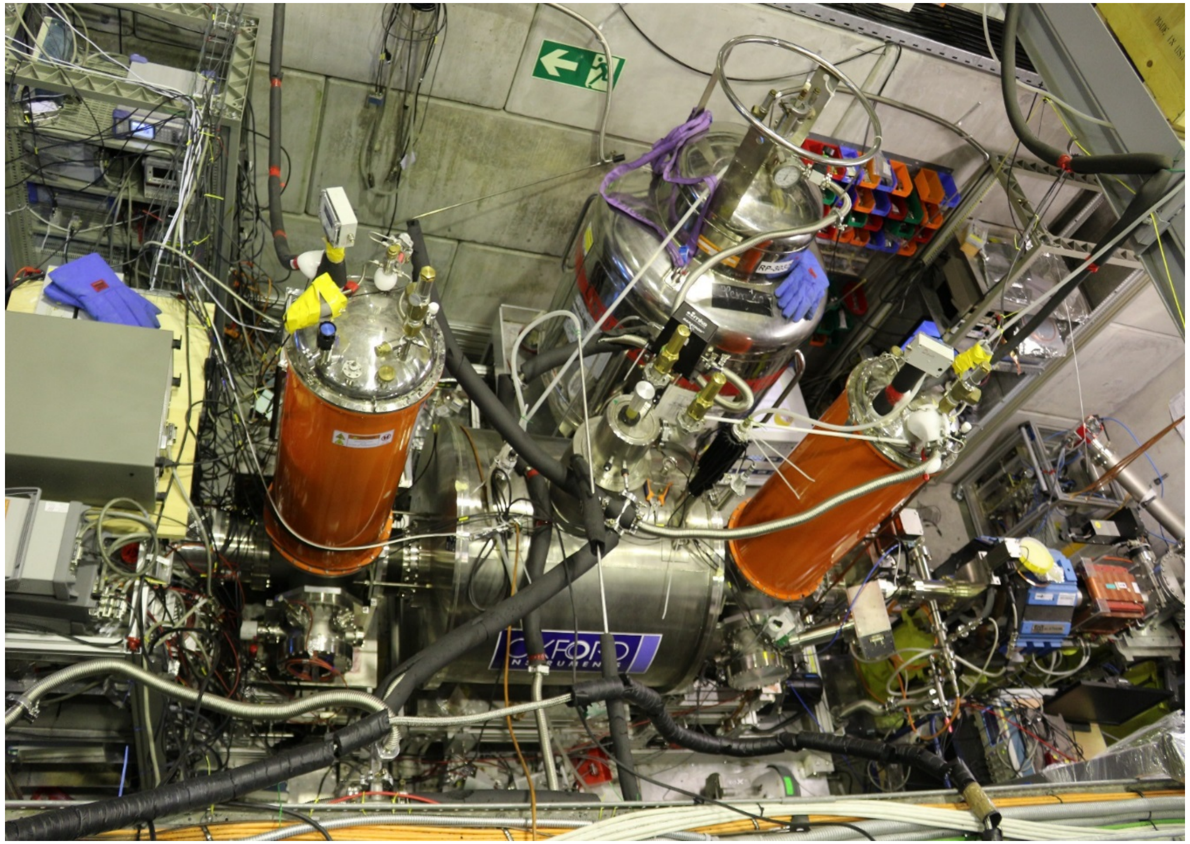


The pinch-off



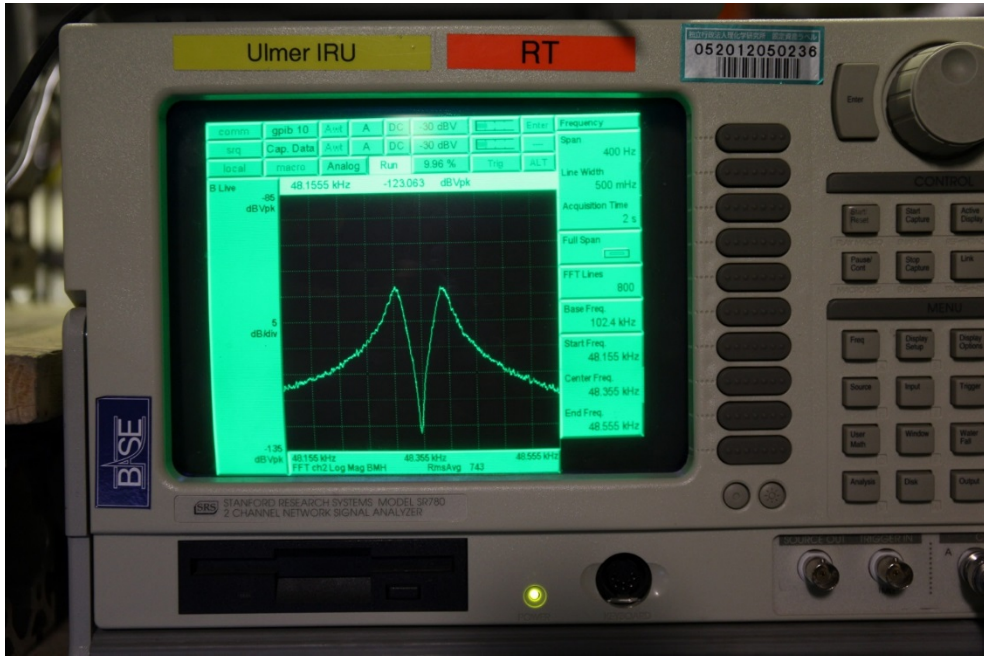
After installation

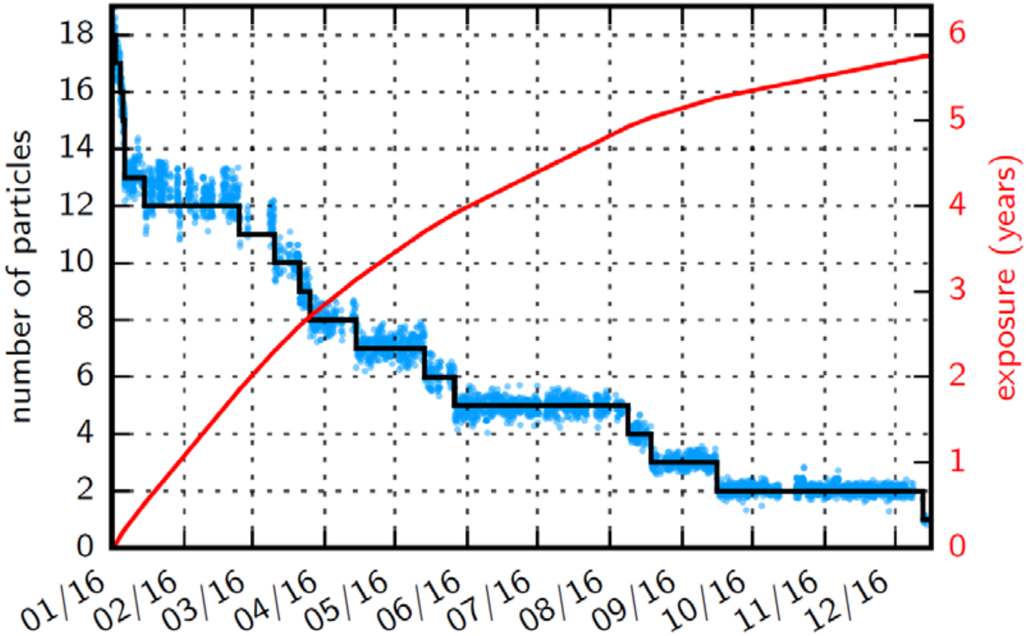




Reservoir trap

Antiprotons stored from 03.11.2015 – 22.12.2016





- Storage of antiprotons for more than one year: **405.5 days**
- Extraction of single particles by a potential tweezer scheme

C. Smorra et al., Int. J. Mass Spectr. **389**, 10 (2015).
S. Sellner et al., New J. Phys. 19, 083023 (2017).

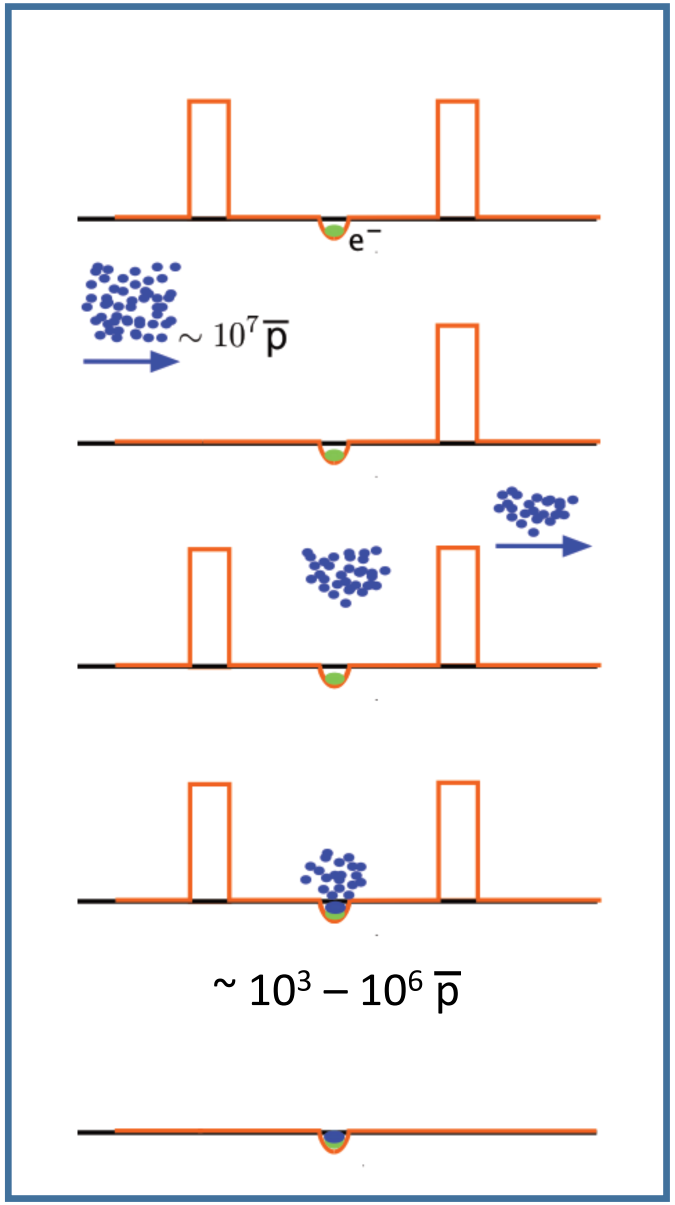
Inversion of the baryon asymmetry:

Antibaryon density: ~ 10^8/cm^3
V < (50 μm)^3
Baryon density: ~ 1 / cm^3
p < 10^{-16} Pa

Sympathetic electron cooling

- Cooling from 1 keV to 1 – 10 meV (10 – 100 K) by sympathetic cooling with electrons
- Electron synchrotron radiation: Cooling time constant ~0.2 s in 1 T

C. Smorra et al., Eur. Phys. J ST 224, 3055-3108 (2015).



Sympathetic cooling limits

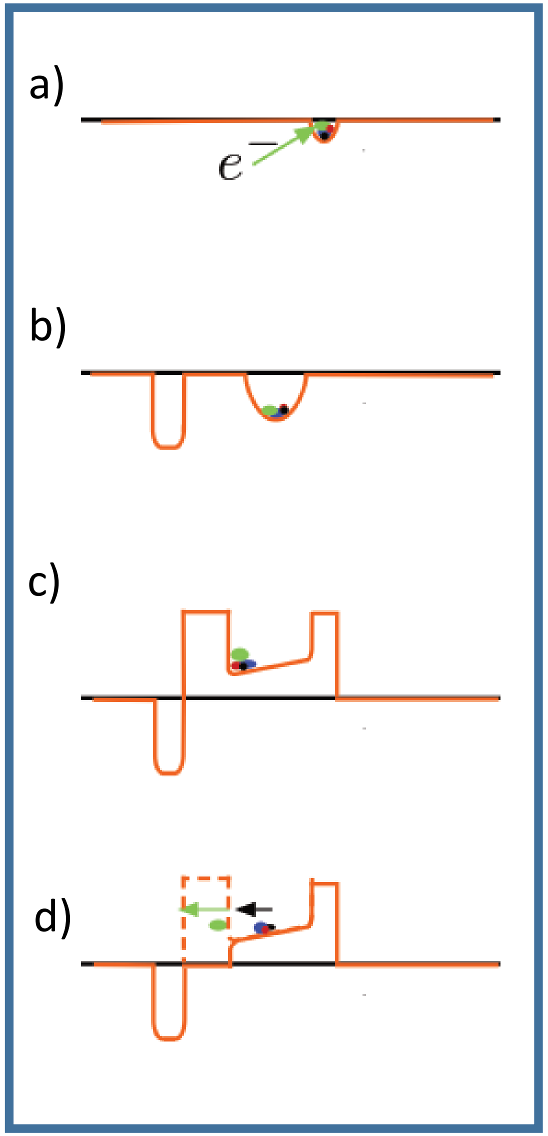
Coulomb interaction reduces
due to centrifugal separation

Electron equilibrium temperature
can be higher that the environment temperature

Radiofrequency noise can excite plasmas
in a broad frequency range

Electron kickout

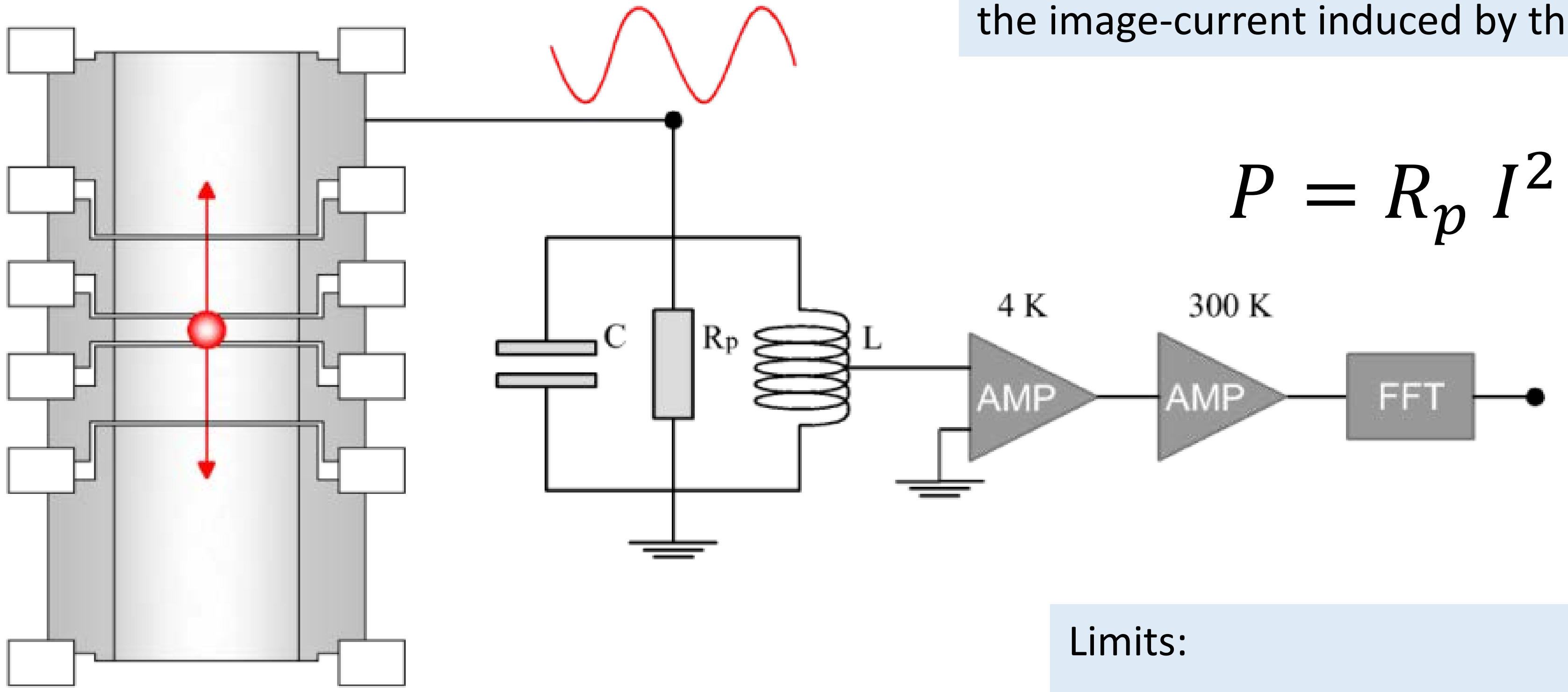
- Elevate the trap potential
- Open for the potential well for a short time (~ 100 ns)
- Electrons are released from the trap
- Antiprotons (and negative ions) remain



C. Smorra et al., Eur. Phys. J ST 224, 3055-3108 (2015).

Resistive Cooling

A resistance in parallel to the trap electrodes damps the image-current induced by the antiproton motion



$$P = R_p\, I^2$$

Limits:

Cooling time: 10 ms (best axial)
20 mins (bad cyclotron)

Temperature: 5 – 10 K

H. Nagahama et al., Rev. Sci. Instr. 87, 113305 (2016).

The challenge: Cooling by ~10 orders of magnitude

Antiproton production: ~ 3.7 GeV

AD final energy: ~ 5.3 MeV

Trap injection energy: < 5 keV

Present cooling limit: 0.5 meV

rf-deceleration

Stochastic Cooling

Electron Cooling

Degrader

Sympathetic cooling

Resistive cooling

Laser-cooled ions?

Mission 1 accomplished

- Cold antiprotons are prepared!
  - High-precision measurements on antiprotons
  - First ingredient for antihydrogen production

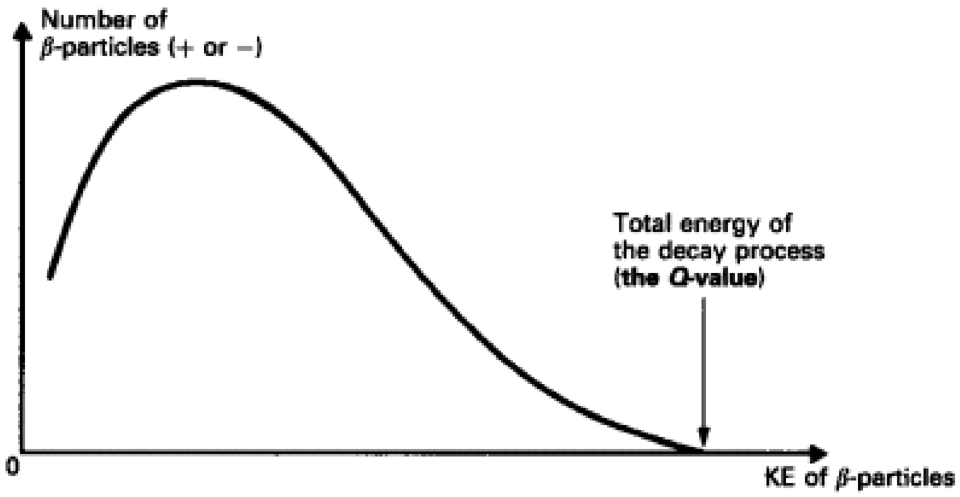
What about positrons?

Positrons production

- Nuclear beta decay provides a natural source of positrons

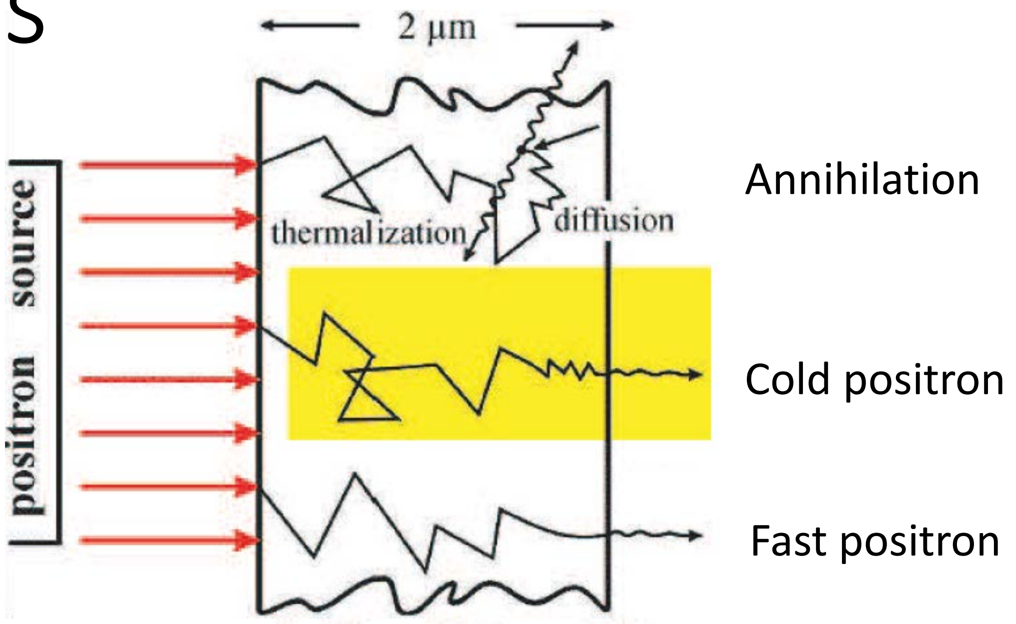
$$(Z, A) \rightarrow (Z-1, A) + e^{+} + \bar{\nu}_e$$

- Three-body decay with about 1 MeV energy release
- Production energy and energy spread unfavourable for trapping



Isotope	Q-value (MeV)	Half-life
^{22}Na	0.54	2.6 yr
^{58}Co	0.47	70.8 d
^{64}Cu	0.65	12.7 h
^{11}C	0.96	20.4 min

Positron interaction in solids



- Positron diffuse in the solid
- Energy loss by inelastic scattering

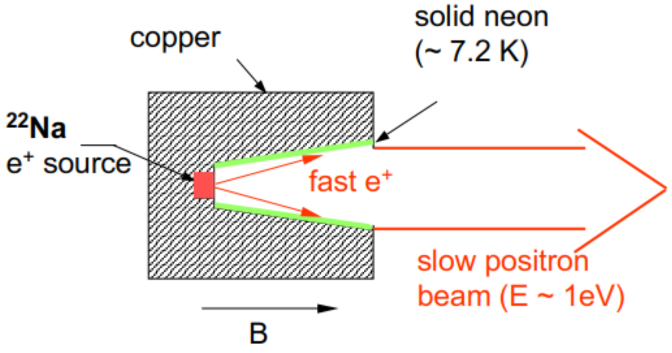
- At low energies:
- Direct annihilation with conduction band electrons in metals (τ < 1 ps)
- Positronium formation and annihilation (τ = 142 ns or τ = 124 ps)
- Trapping of positions in crystal defects and annihilation

We need a non-conducting, defect-free crystal with high threshold for positronium formation

Moderation of positrons

Moderators to Produce Slow Positrons

Frozen noble gases (Ne, Ar, Kr) most efficient



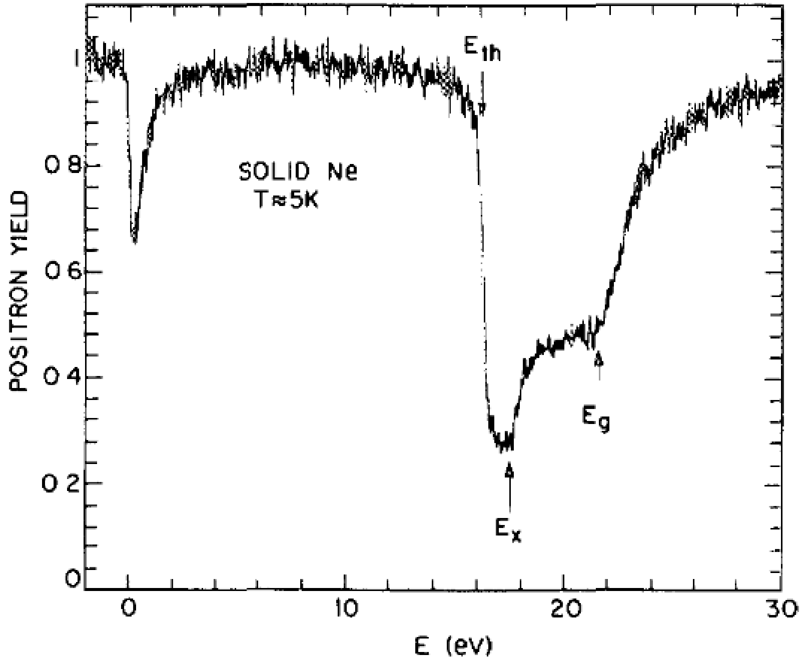
Efficiency: Neon ~ 1%

100 mCi ^{22}Na ~ 10^7 slow e^+/s (1 pA)

Metals (Cu, W) are reasonably good moderators too
but ≤ 0.1 % efficient

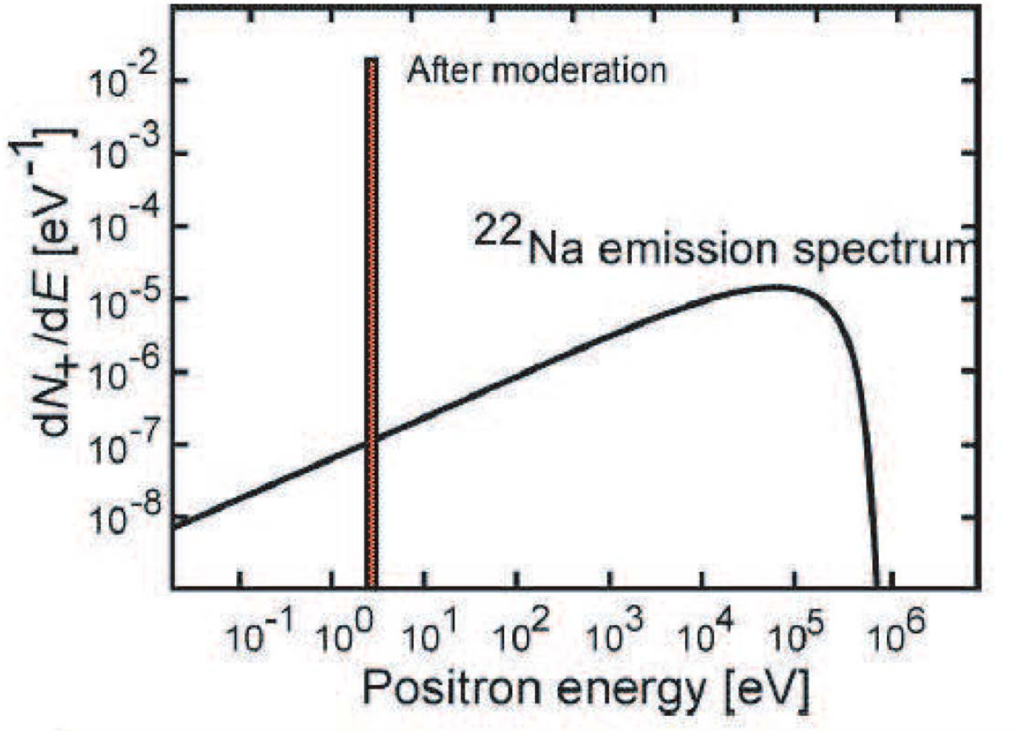
Courtesy of C. Surko

- Solid noble gases have a large band gap
- Positrons can only thermalize by phonon emission
- Annihilation and positronium formation surpressed



A.P. Mills et al., Appl. Phys. Lett. 49, 1121 (1986).

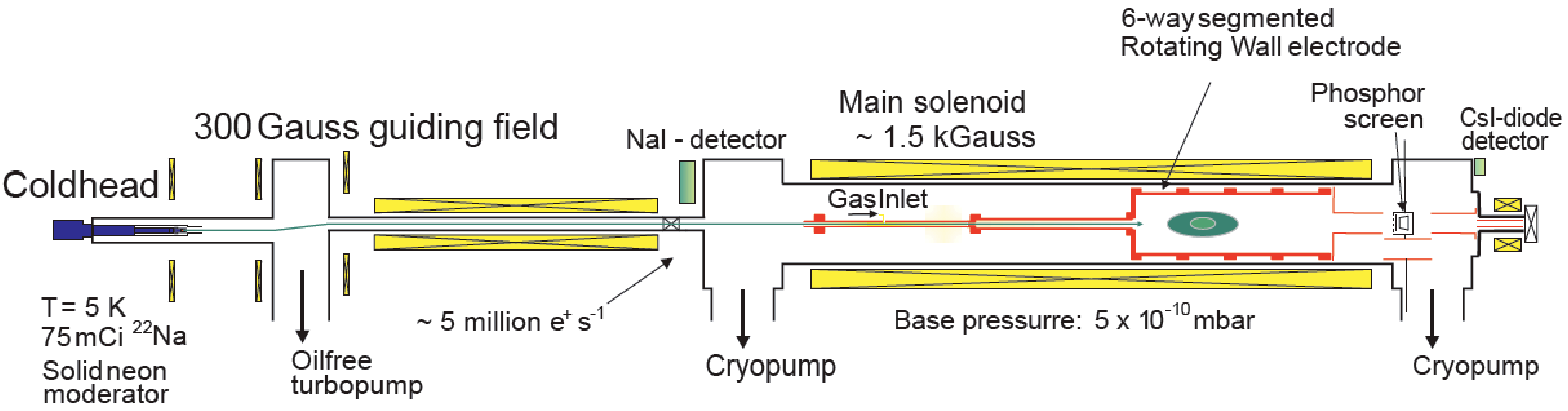
Energy spectrum after moderation



Positron energy:
~ 1 eV

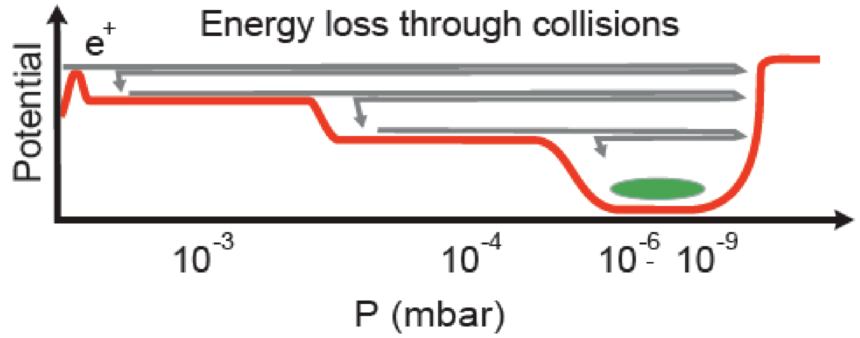
Energy spread:
~ 0.5 eV
~ 6000 K

Surko-type positron accumulator



Buffer-gas cooling with N2:
Lowest electronic transition: 8.55 eV
Positronium production threshold: 8.78 eV

Synchrotron radiation cooling in magnetic field



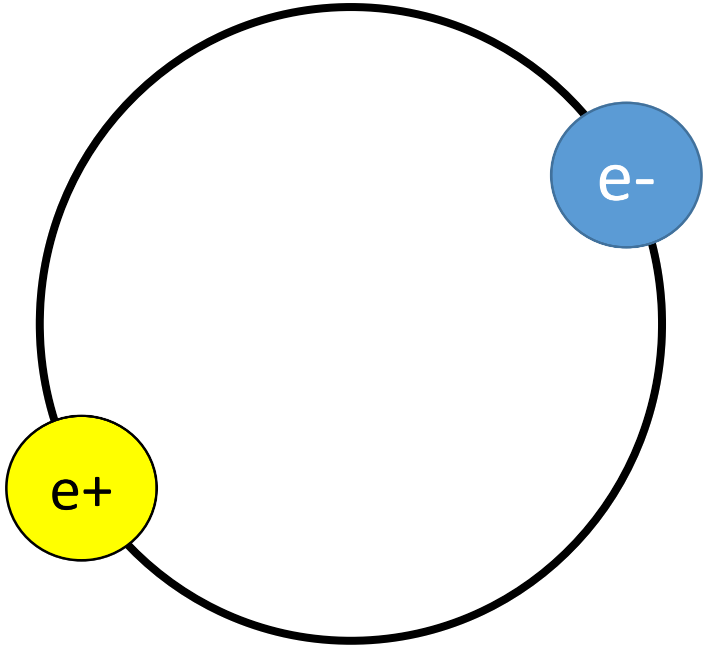
Typical temperatures in an accumulator: 10 K – 100 K

http://alpha.web.cern.ch

Some notes on positronium

- Positronium is a hydrogen-like atom
- Spectroscopy on positronium allows high-precision tests of quantum electrodynamics
  - No uncertainties due to finite proton size!
- Most accurate determination of the positron mass comes from the 1S-2S spectroscopy of positronium
  - High-precision CPT test with leptons ($\delta m/m \sim 8\ 10^{-9}$)
- Rydberg positronium can be used to produce cold antihydrogen by charge exchange:

$$Ps^* + \bar{p} \Rightarrow e^+ + \overline{H}^*$$



Mission 2 accomplished

Cold positrons can be prepared!

Now we can make antihydrogen!

TO BE CONTINUED

Antihydrogen Experiments