Gravitational Behaviour of Antihydrogen at Rest

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Standard Model of the Universe

(Some) open questions

- What are dark matter & dark energy ?
- Why antimatter disappeared ?
- Quantum theory of gravity ?
- …

still many problems unanswered !

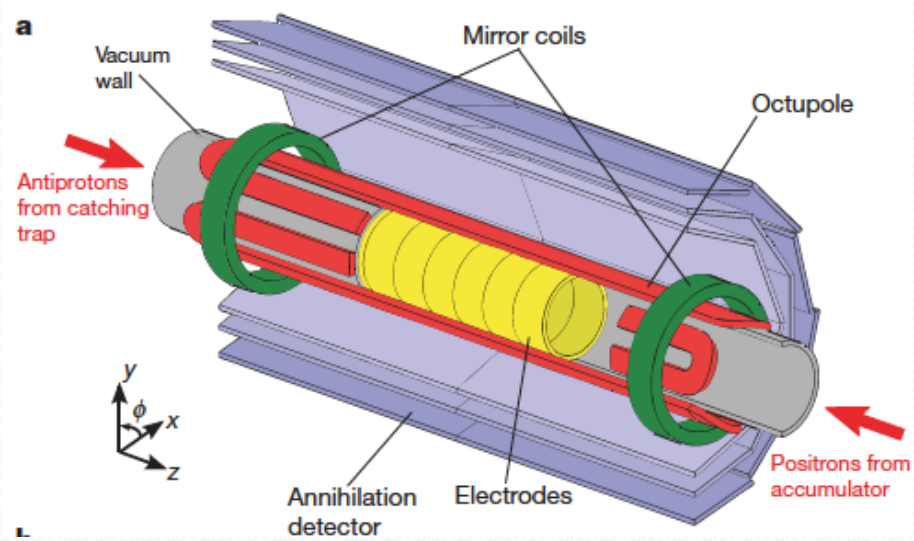
Gravity may be the least understood fundamental force ?

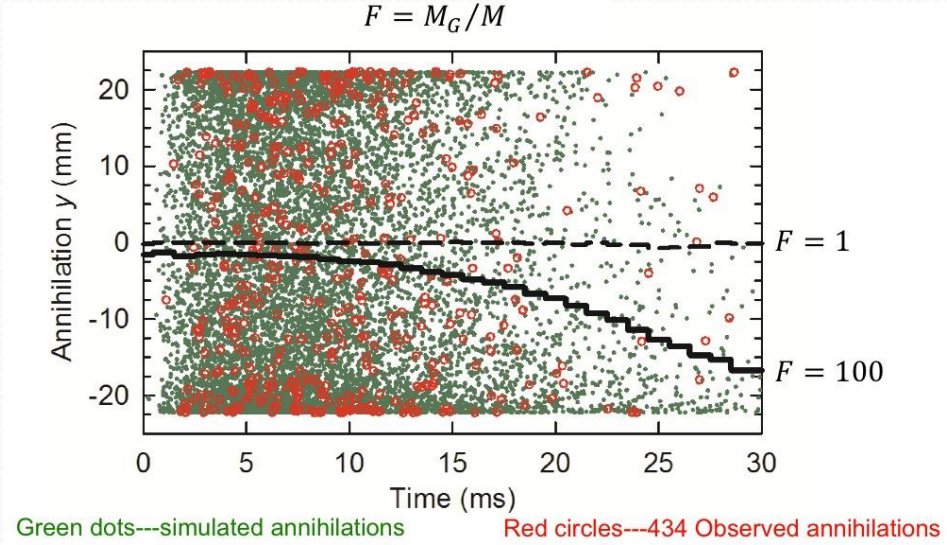
Free Fall

Gravitational force between matter and antimatter ?

Experimental Aspects

ALPHA collaboration, C.Amole et al. Nature Comm. 4, 1785(2013)





magnetic trap : neutral antihydrogen atoms through interaction with their magnetic moments

-65<F<110

New opportunity for antimatter gravity based on anti-Hydrogen atoms

However temperature of anti-Hydrogen is too high !

Experimental Aspects

Classical free fall: $z = z^0 + v_z^0\, t + \frac{1}{2}\, g t^2$

Main perturbation

Desired range

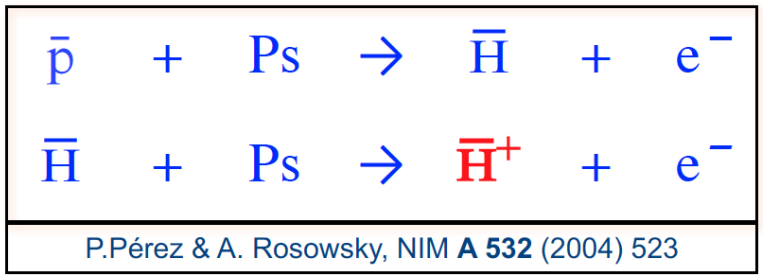
Velocity fluctuation	100 m/s	3 m/s	0.1 m/s
Temperature equivalent	1 K	1 mK	1 μK

Recoil limit of Ly_α laser cooling of $\bar{H}$

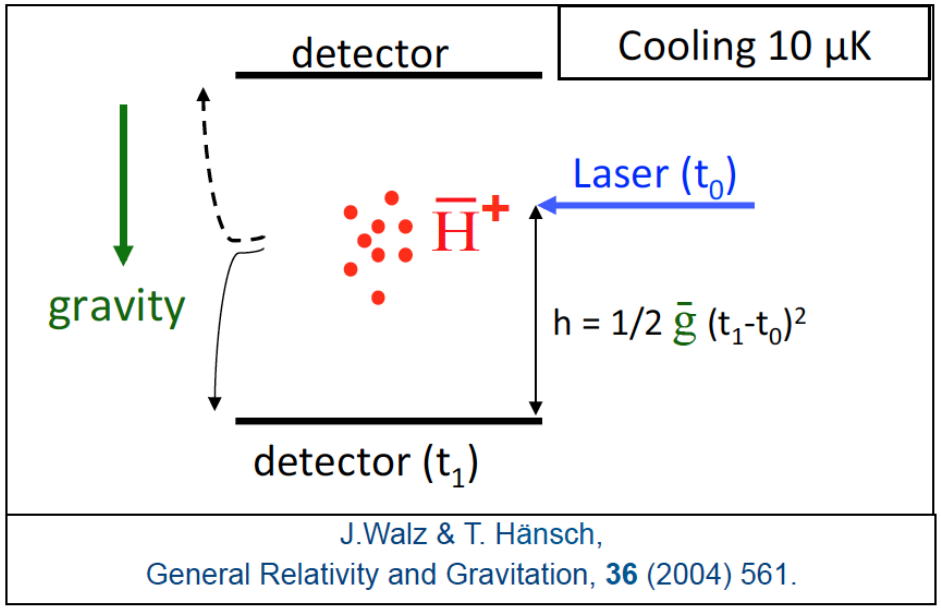
Necessary to cool anti-Hydorgen below 1 mK

New Idea : GBAR Concept

- Produces $\bar{H}^+(\bar{p}e^+e^+)$ instead of $\bar{H}(\bar{p}e^+)$
- Trap and cool $\bar{H}^+$ down to 10 µK
  (Sympathetic cooling with Be^+)
- Photodetachment of e^+
- Free fall of $\bar{H}$

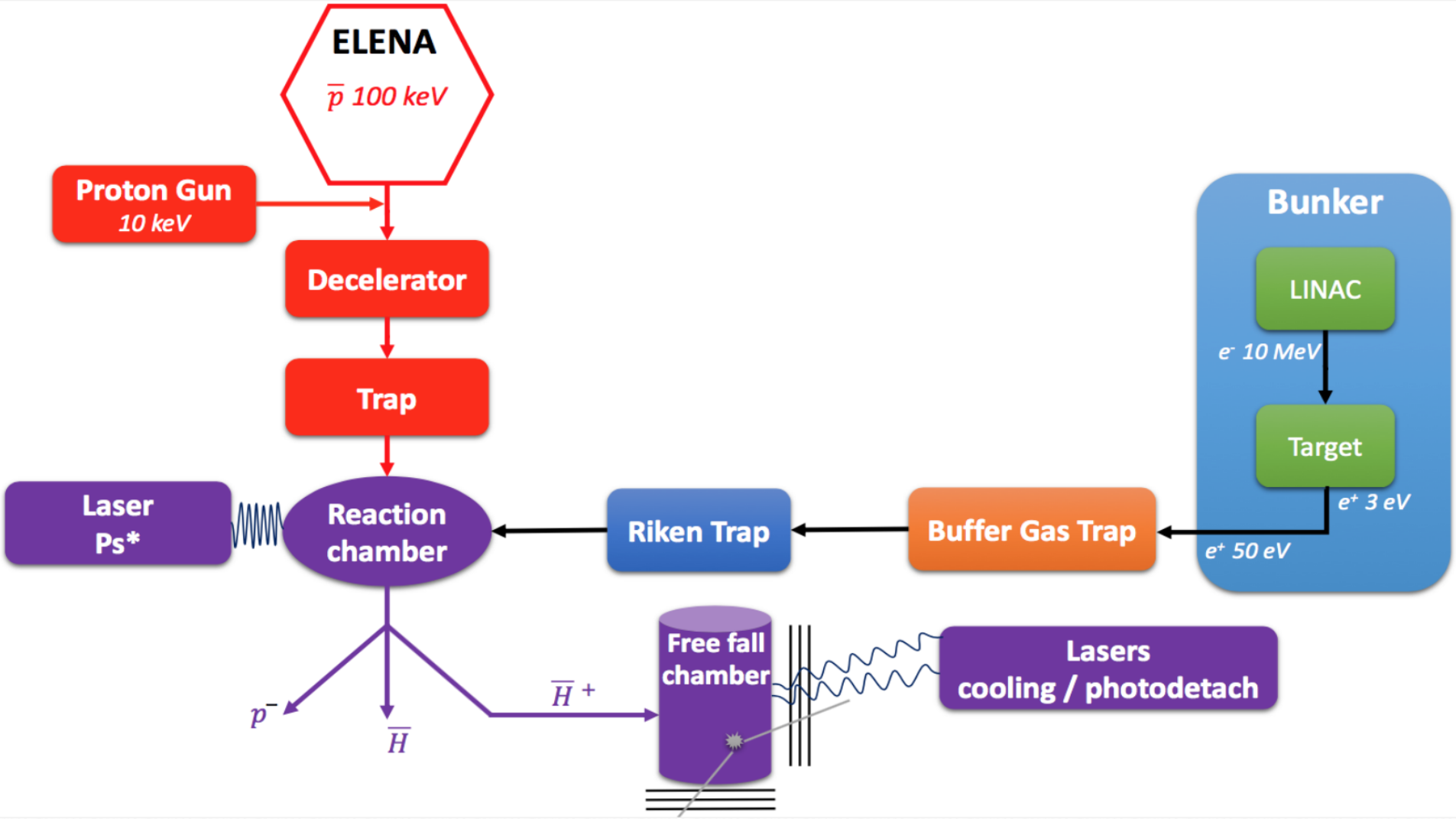


P.Pérez & A. Rosowsky, NIM **A 532** (2004) 523

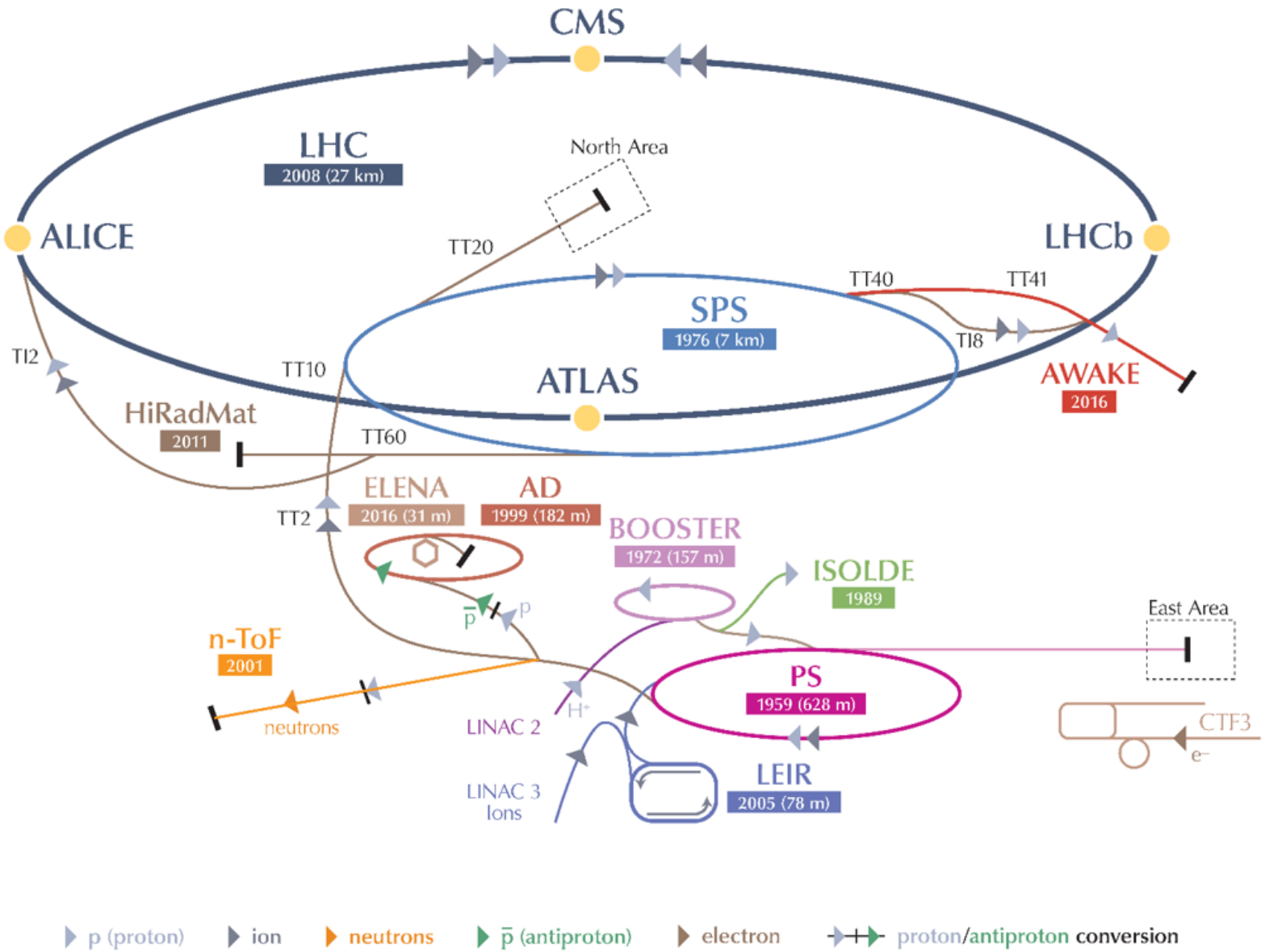


J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561.

GBAR Experiment Scheme

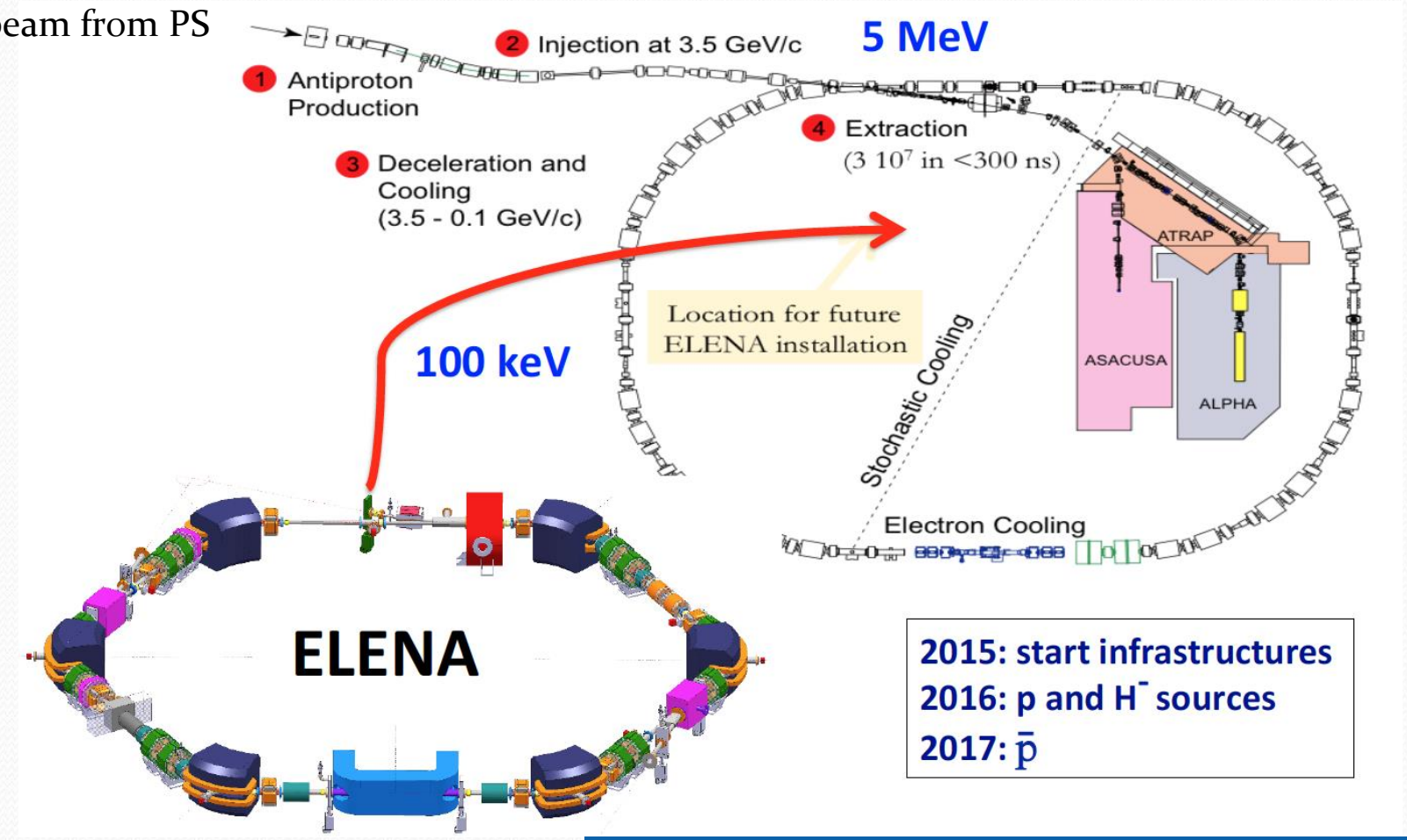


CERN's Accelerator Complex



Antiprotons from CERN AD/ELENA

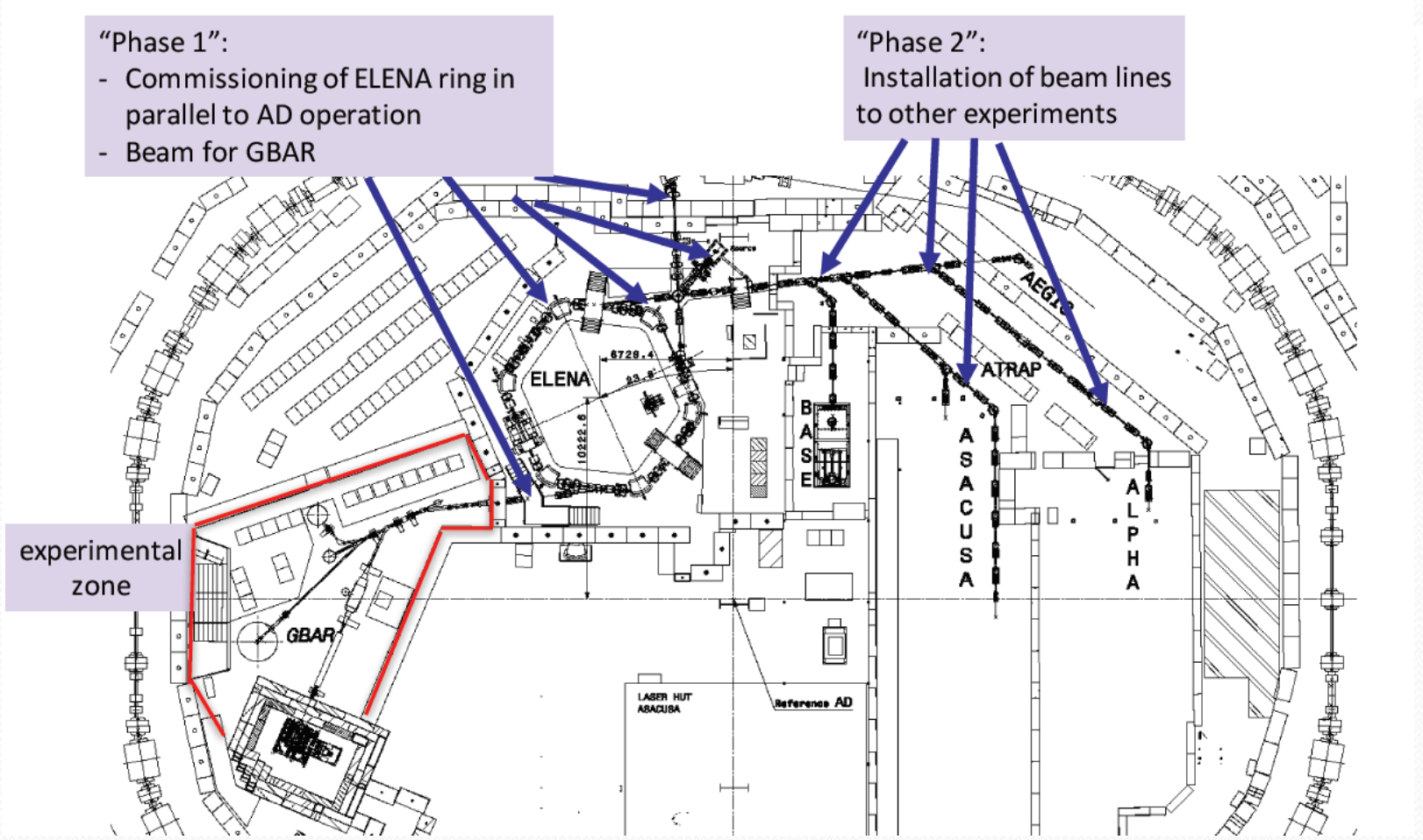
26 GeV p beam from PS



ANTIMATTER FACTORY

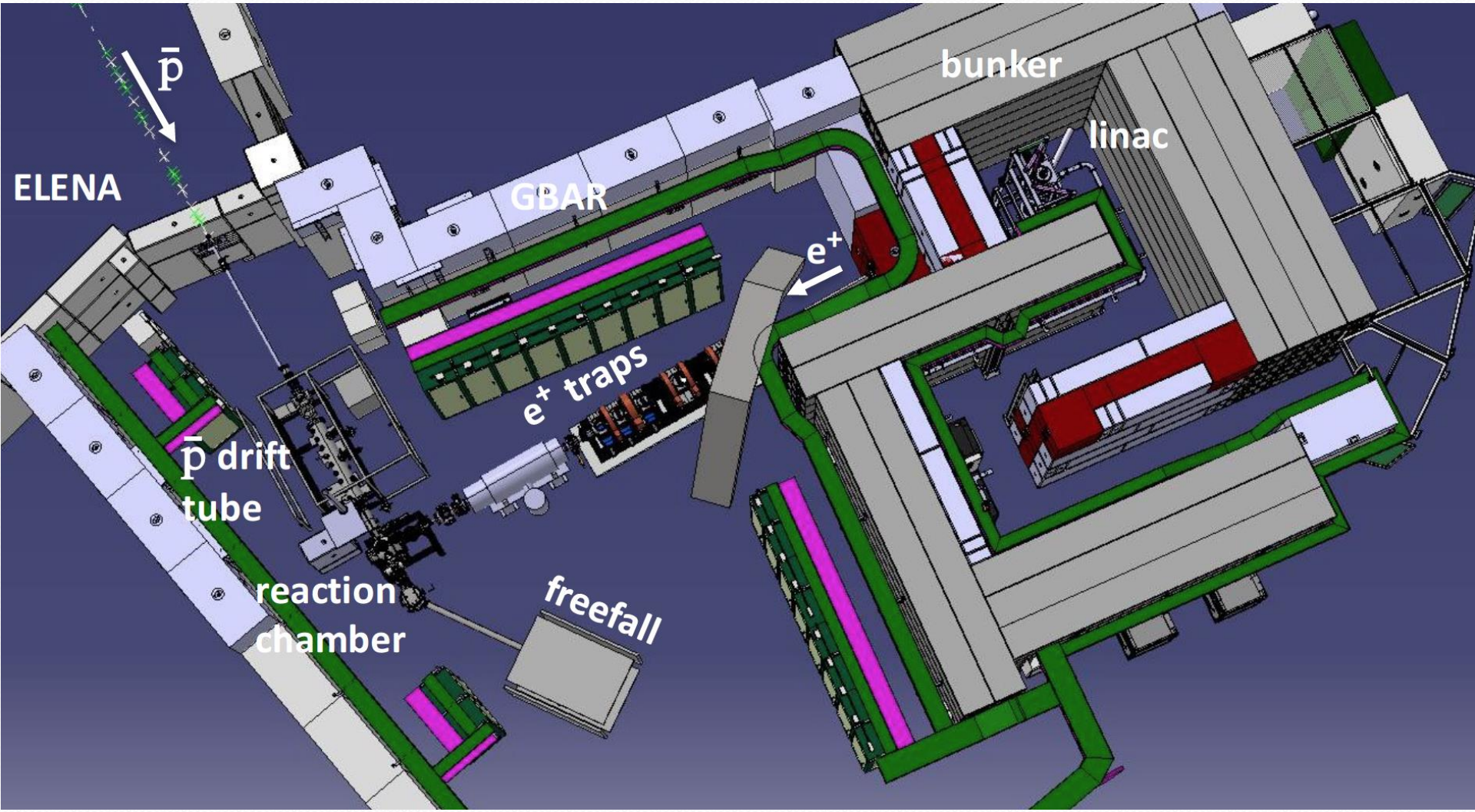
ELENA

Antiprotons from CERN AD/ELENA

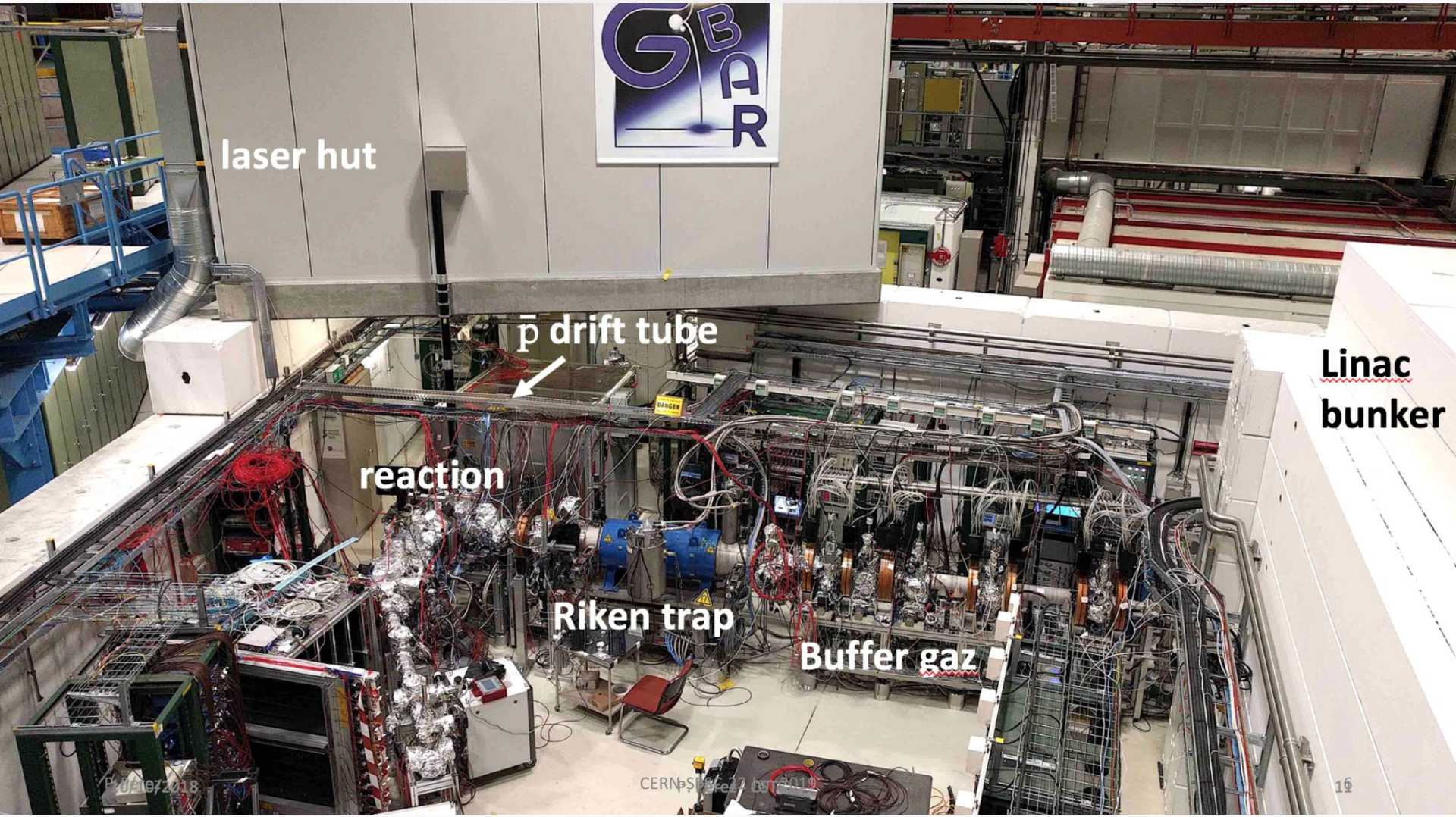


GBAR Preparation

GBAR Preparation

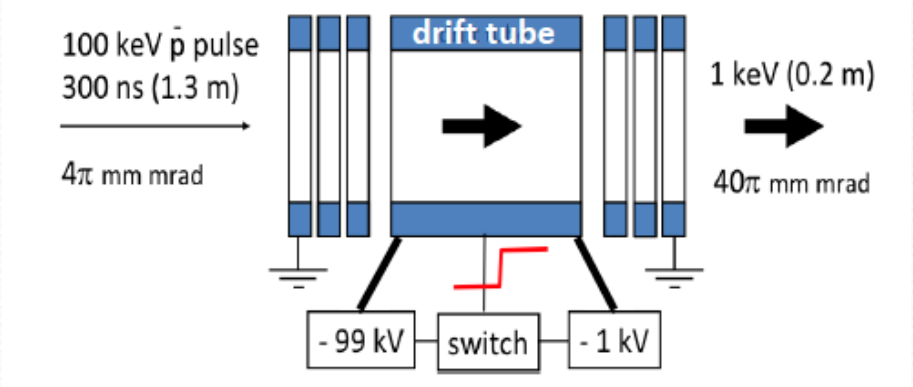


GBAR Preparation

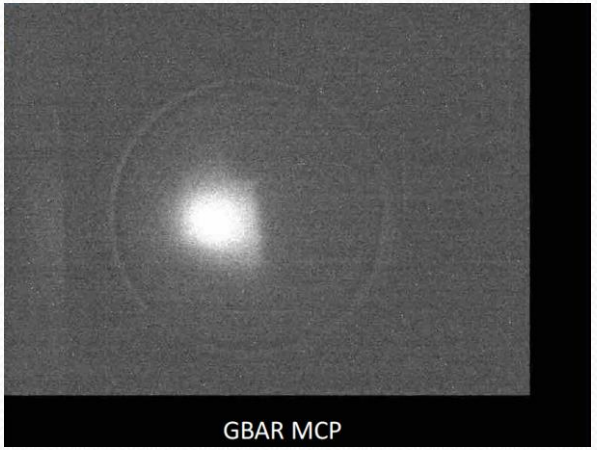


Antiprorton Preparation (Decelerator)

GBAR need pbar at ~ 1 ~10 keV
100 keV from ELENA to be decelerated

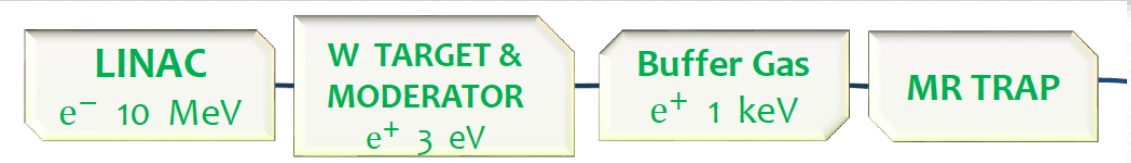


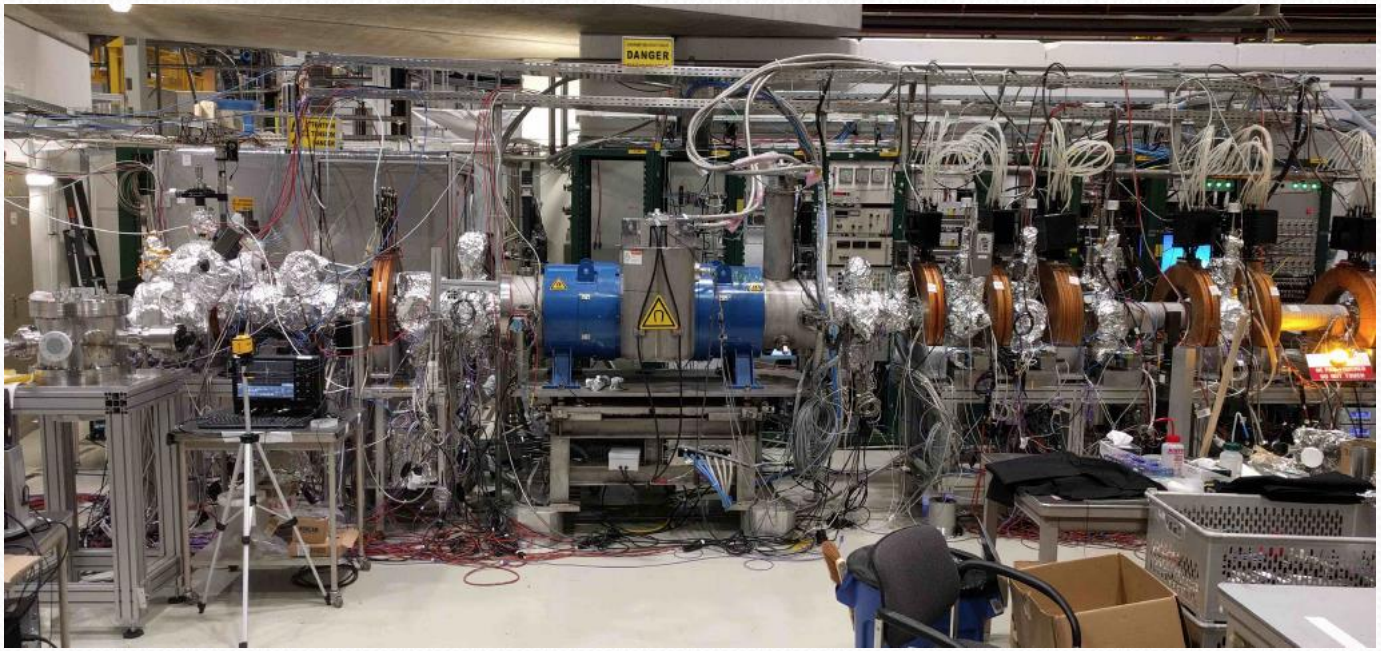
Installed at CERN



First beam (July 20, 2018)

Positron generation (LINAC)





Installed at CERN

With linac at 100 Hz → 1 x 10^8 e^+ in 100 s

e^+ lifetime in trap > 20 min

Goal:

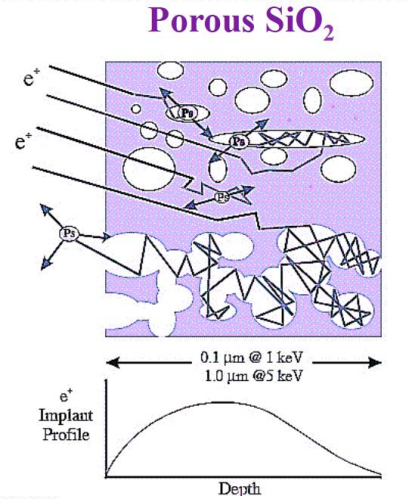
accumulate 3 x 10^{10} e^+ in 110 s

9+ MeV/0.2 mA electron linac
Installed at CERN in 2017

2×10^7 e^+ / s (100 Hz)

Goal 3×10^8 e^+ / s

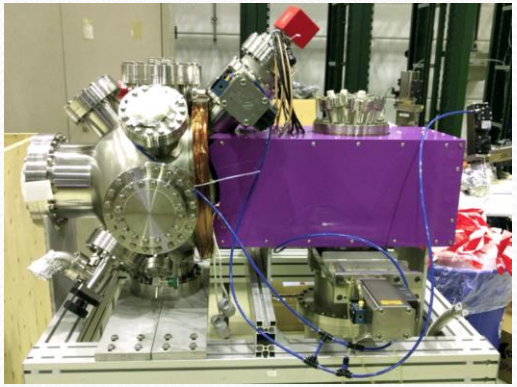
Anti-Hydrogen Ion Production

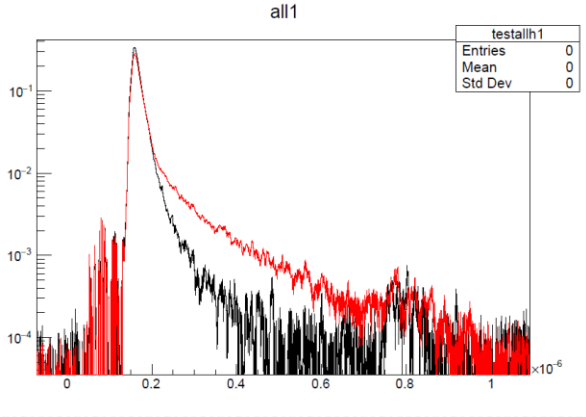


@CEA: 10^{10} Ps/cm^3 $\Rightarrow$ 10^8 e^+
@CERN: 10^{12} Ps/cm^3 $\Rightarrow$ 10^{10} e^+

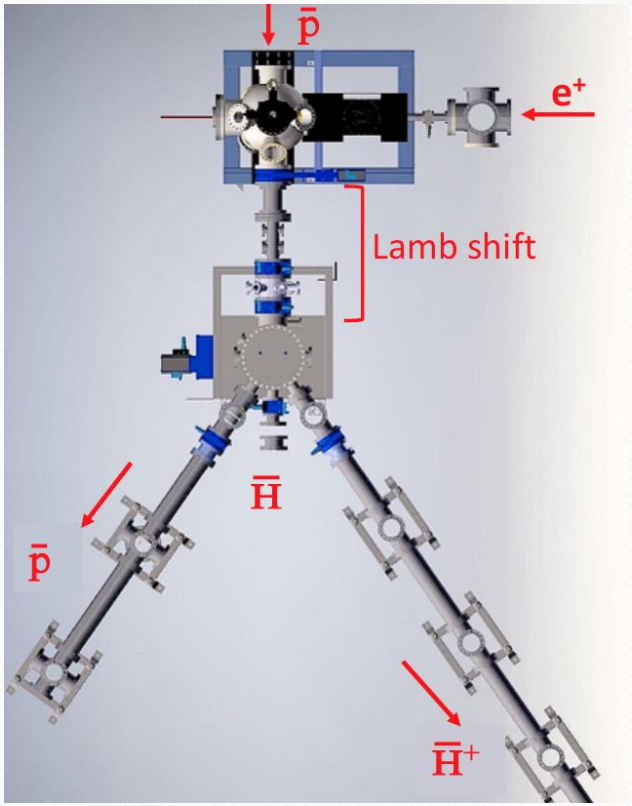
$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$

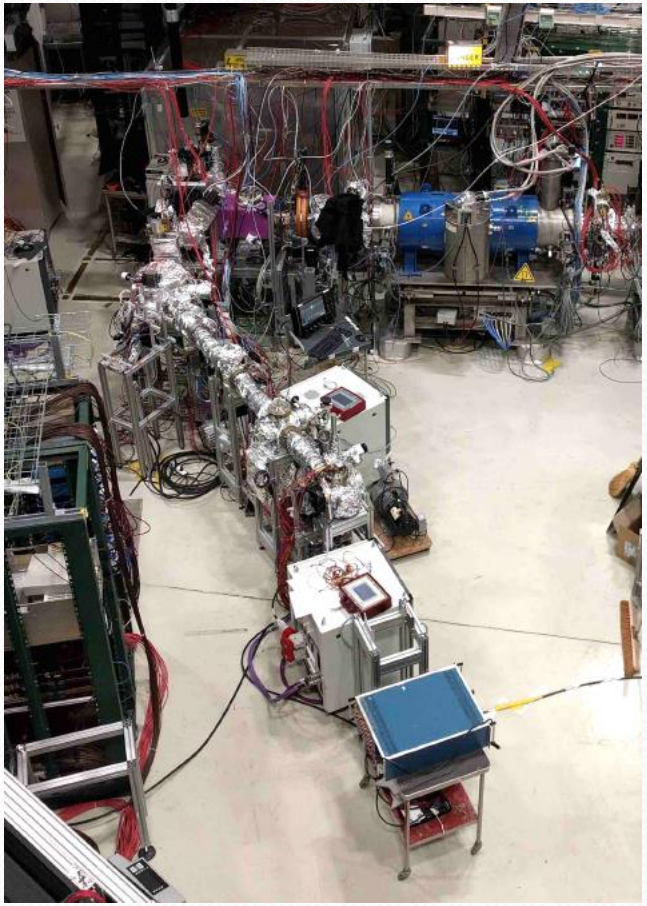
$$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$$





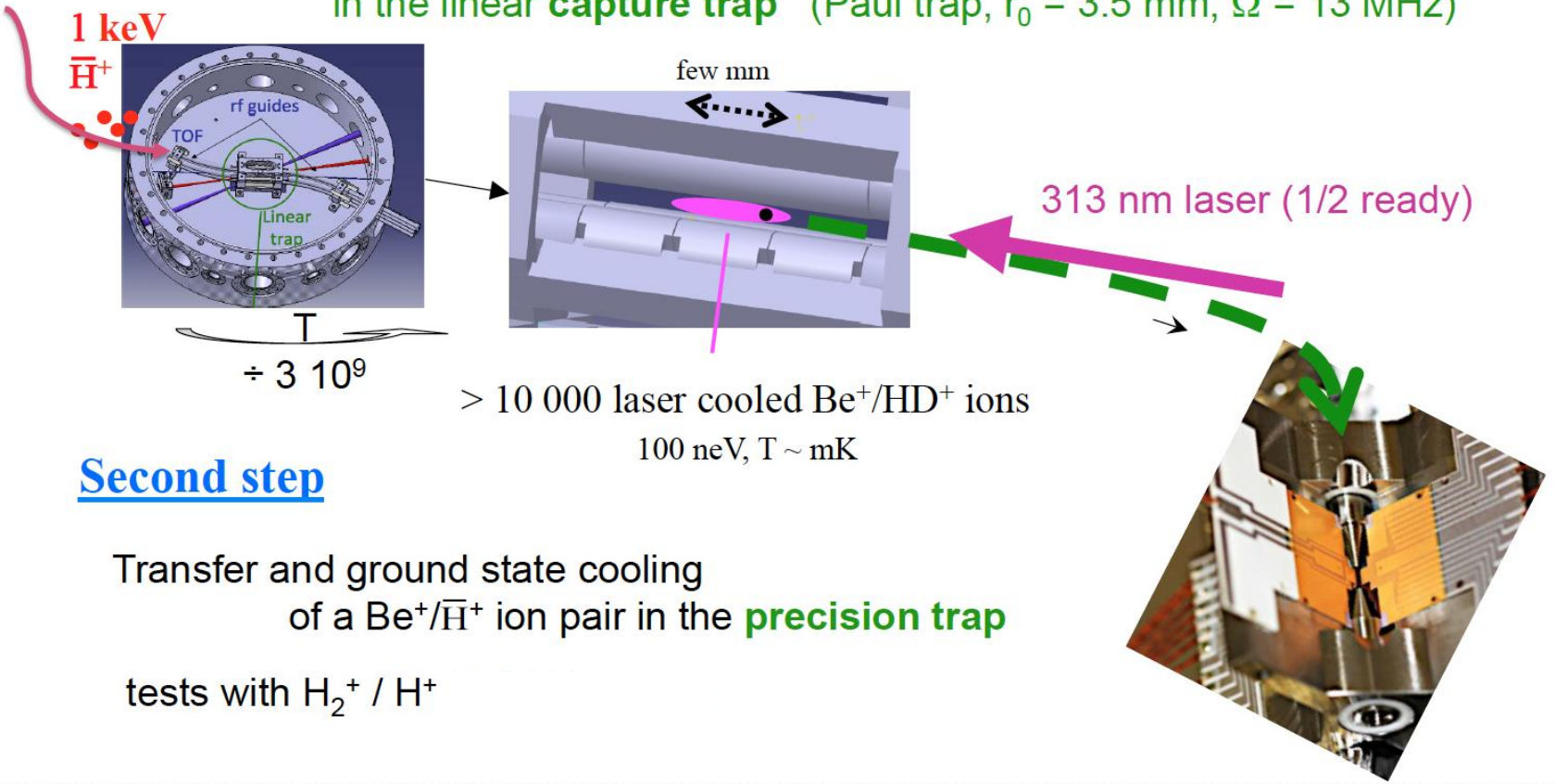
Anti-Hydrogen Ion Production





Cooling anti-Hydrogen ions

First step Capture and sympathetic Doppler cooling by laser cooled Be^+ ions in the linear **capture trap** (Paul trap, r_0 = 3.5 mm, Ω = 13 MHz)



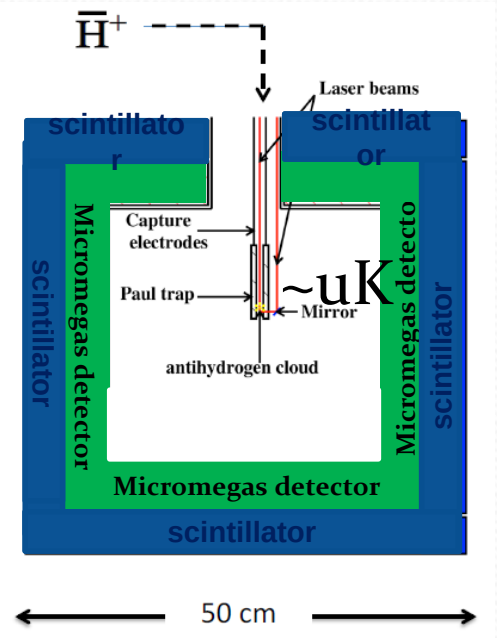
Second step

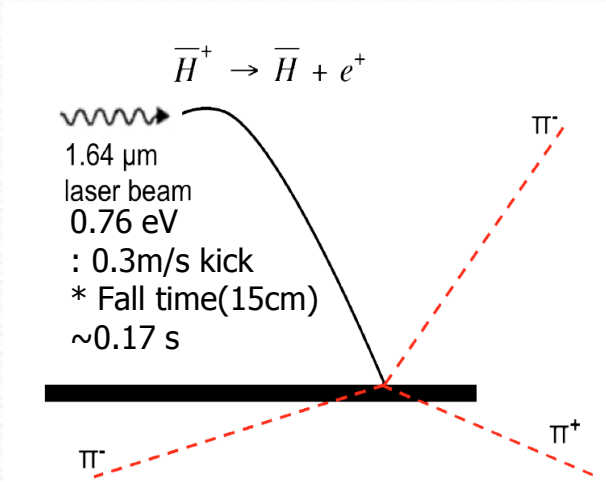
Transfer and ground state cooling
of a $Be^+/\bar{H}^+$ ion pair in the **precision trap**

tests with H_2^+ / H^+

GBAR Free Fall Measurement

Detect charged pions from anti-Hydroegn annihilation !





Detection	Requirement
TOF precision	150 μs
Annihil. vertex precision	2 mm
Background rejection	event topology

To measure the gravitational acceleration, we need to measure the free fall time and the position of the annihilation is happened : tracker + TOF

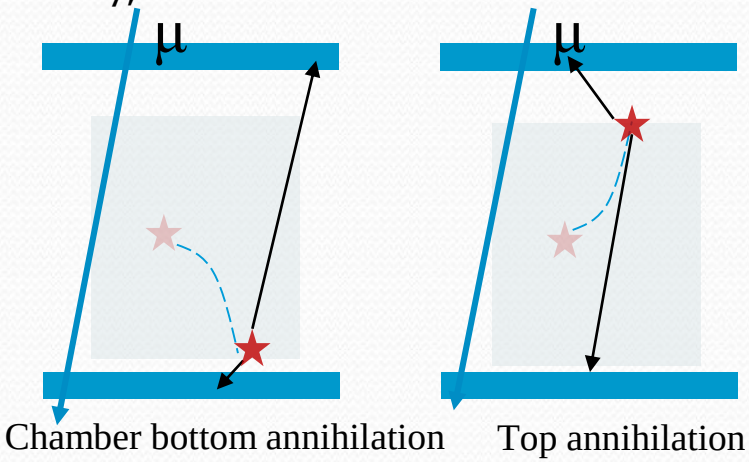
Free Fall Measurement (TOF)

To measure the gravitational acceleration, we need to measure the free fall time and the position of the annihilation is happened

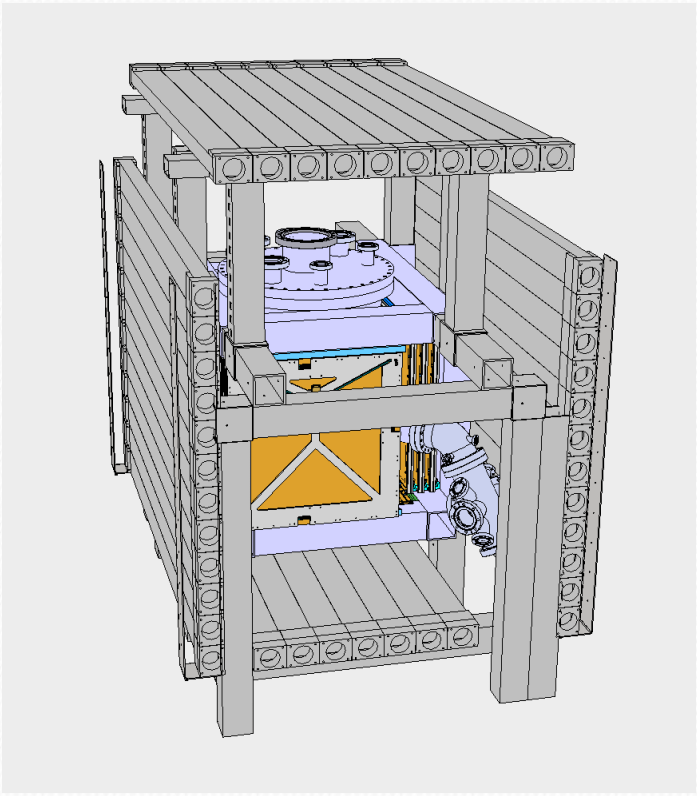
An array of plastic scintillation counters.

One bar = 10*5*170 cm^3
One counter = (PMT) – (plastic bar) – (PMT)
One wall (left/right) : 12 counters
(top/bottom) : 10 counters
* It can be changed, depending on FFC

Totally, 44bars and 88PMTs



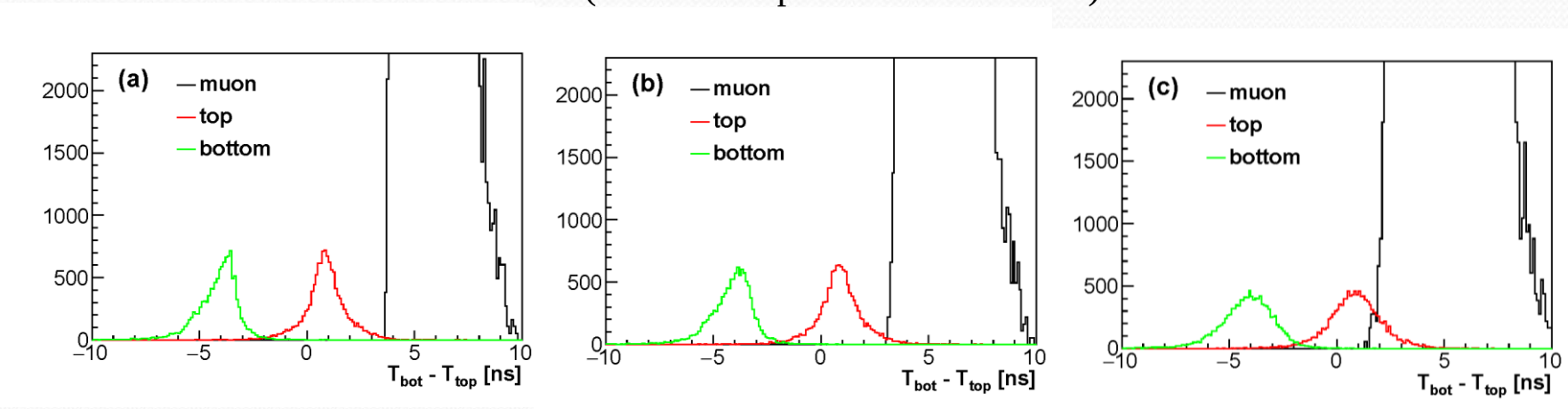
Chamber bottom annihilation Top annihilation



GBAR Free Fall Measurement (TOF)

TOF requirement

3-pi decay events, 825mm height
(normalized pion:muon = 1:5500)



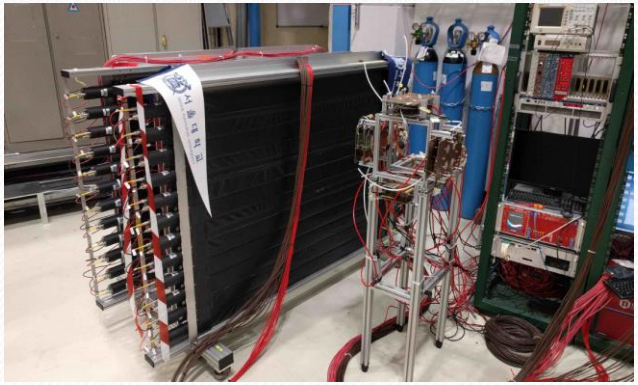
(a) 0.1 ns (b) 0.2 ns (c) 0.5 ns

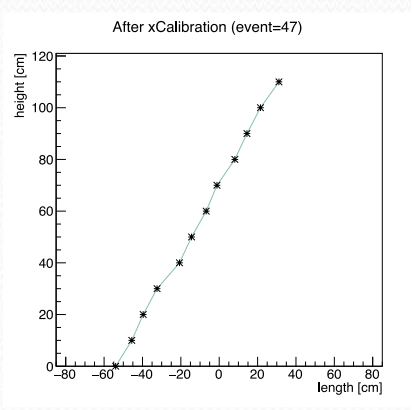
T_1 = time to bottom TOF
T_2 = time to top TOF
dT = $T_1 - T_2$

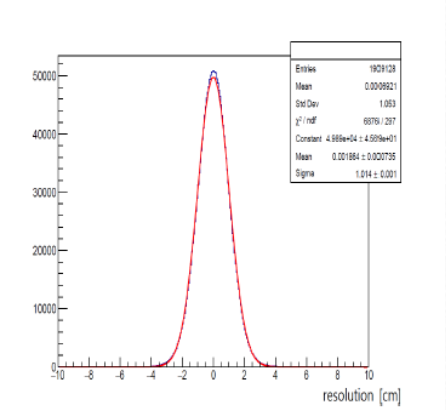
For efficient cosmic ray rejection, the time resolution should be better than 0.2ns.

TOF

Two walls of TOF counter array was installed at CERN (2018)

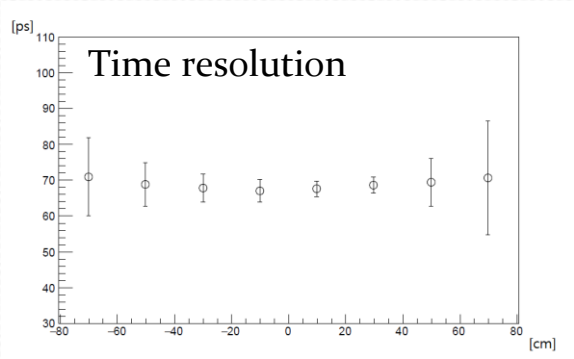






Test with cosmic ray muons

- Test DAQ system
- Test the performance of counters



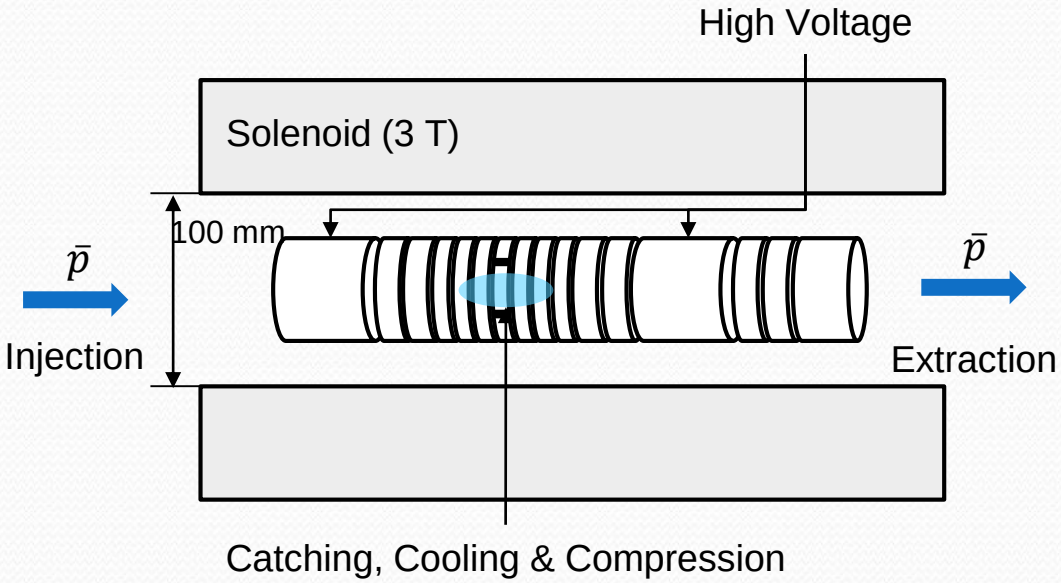
Performance : Spatial resolution along the length of scintillator bar ~ 1cm

Time resolution ~70 ps

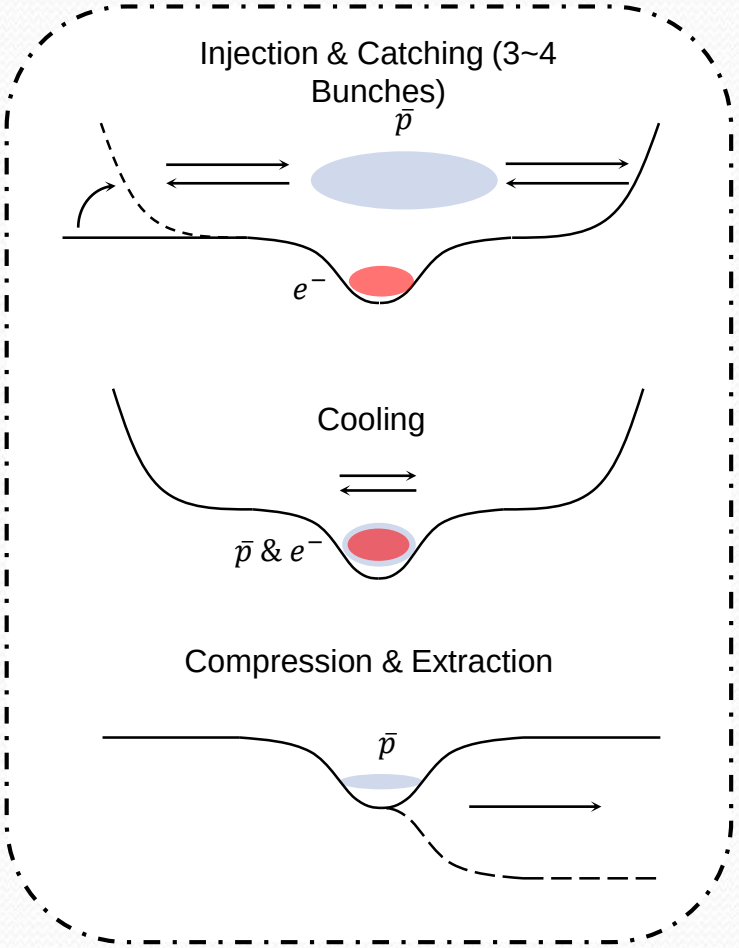
p-bar trap

Penning-Malmberg trap

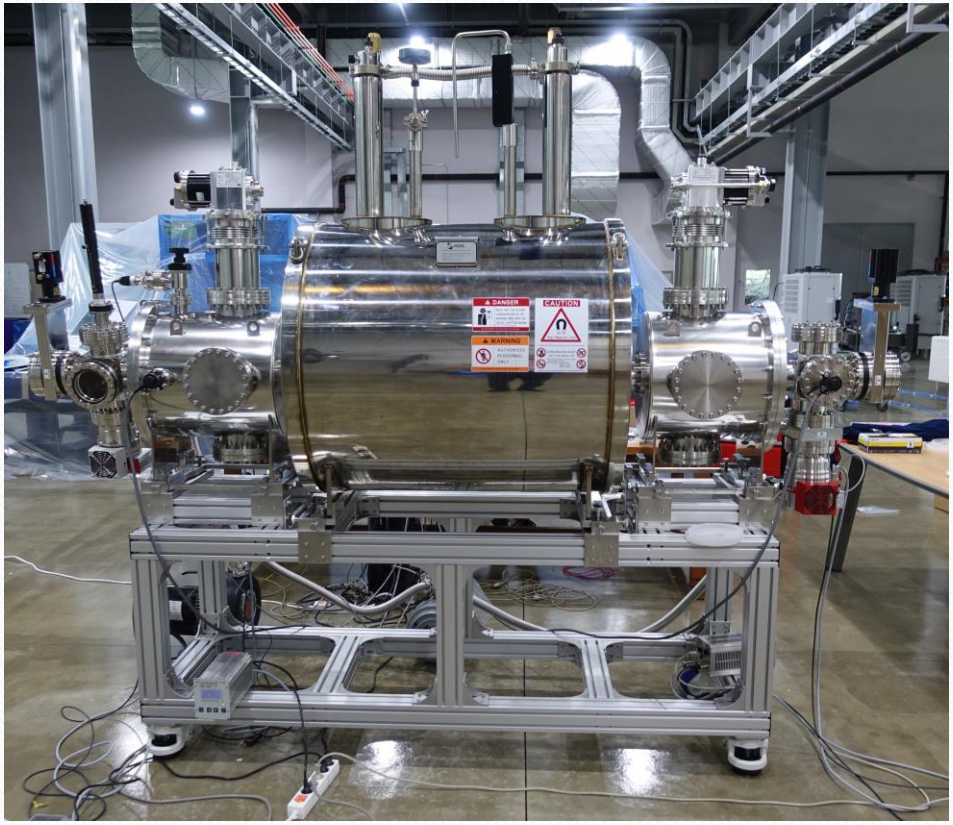
- High magnetic field, multi-ring electrodes for field shaping
- electron cooling by synchrotron radiation
- antiproton cooling with electrons
- Radial compression with rotating wall
- High vacuum (~ 10^{-12} mbar)



< Scheme of Antiproton Trap >



p-bar trap



Used magnet from
KU Chemistry (S.W.Lee)
(7T Super Conducting Solenoid)

Cold UHV pipe fabricated

Trap electrodes fabricated

Assembly with magnet tested

Magnet was shipped to CERN this week

Control system is developed

Other parts of the trap will be shipped to CERN at the end of this year

Test with proton/H- beam during LS2

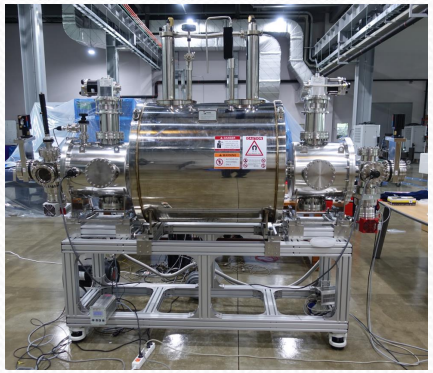
Antiproton will be available again in 2021

Korean Team

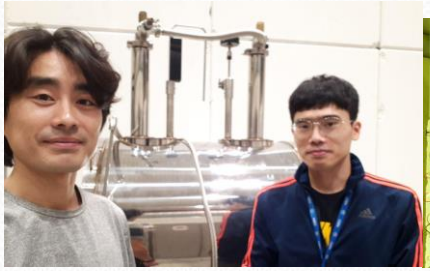
Seoul National Univ : 2 Ph.D. (S.K.Kim, B.H.Kim) + 3~4 GS
Korea Univ : 1 Ph.D. (E.S.Kim) + 1 GS
UNIST : 1 Ph. D. (M.Chung) + 1 GS
IBS : 2 Ph.D. (J. Lee, Y.Ko)

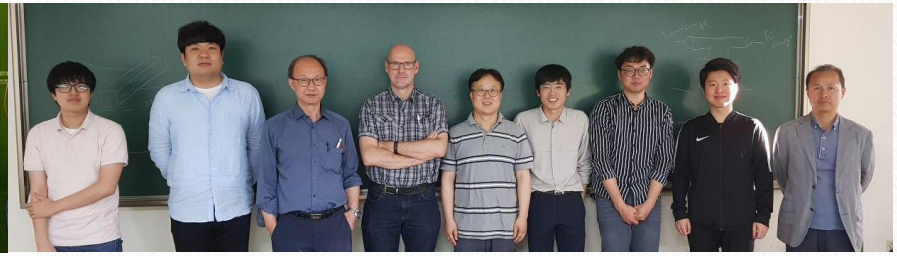
Total : 6 Ph.D.s + 5~6 GS
(*GBAR ~66)

TOF detector (Full)
Antiproton trap(Full)
Positronium flux monitor



* Common Fund : 4.7 kEuro/Ph.D.





Free Fall

Before Galileo Galilei nobody doubted ….

Need the same experiment with matter and antimatter…