The GBAR experiment at CERN

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Measuring the effect of gravity on anti-matter

- **Why?**
  - **Anti-matter well known, e^+ used everyday in PET-scanners**

  Particle/antiparticle pairs produced since very long in high-energy experiments

  $\bar{p}$ made everyday at CERN, precision measurements on magnetic moment, etc.

  Anti-hydrogen recently made and trapped. Measured 1S-2S transition (ALPHA, 2 10^{-12})

  …but no measurement of gravity!

  - **Standard Field Theory : same as matter.**

  Several arguments, see famous review by Goldman-Nieto (1991)
    - Theory: Energy conservation, equivalence principle
    - Experiment: indirect tests
      - $\bar{p}$ cyclotron frequency
      - K^0-$\bar{K}^0$ oscillation
      - Neutrinos/antineutrinos from SN1987A

Measuring the effect of gravity on anti-matter

- **But!**
  - Matter/ Anti-matter is a pure quantum effect, and Gravity and quantum mechanics do not go along well…
  - One interesting interpretation of the accelerated expansion of the Universe as a matter/antimatter symmetric universe with anti-gravity
- **How?**
  - Charged particles: $\bar{p}$, e^+ : EM forces (much) too large
  - Neutrals: $\bar{n}$ difficult to slow down, Ps (e^+-e^-) short lifetime, polarizability…)
  - Antihydrogen: very natural test for antimatter, difficult but feasible
- **Which accuracy?**
  - Sign: test for “antigravity”
  - $\bar{p}$ mass mostly from gluons. Test q/$\bar{q}$ masses? => 1% accuracy

Principle of GBAR at CERN

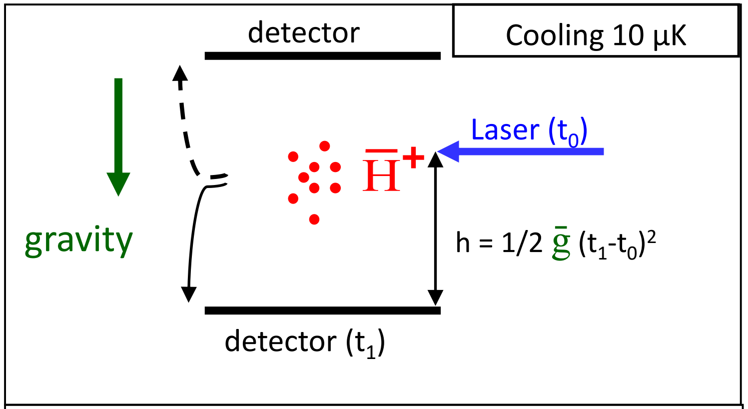
- **Produce a high density *positronium* (Ps) plasma**
- **Use slow antiprotons ($\bar{p}$) from new ELENA ring at CERN**
  - **[decelerated, stored in $\bar{p}$ trap]**

- **Enable two reactions:**
  1) **$\bar{p}$ + Ps => $\bar{H}$ + e^- *[intense source of $\bar{H}$ atoms for other measurements]***
  2) **$\bar{H}$ + Ps => $\bar{H}^+$ + e^- [possibly enhanced with laser Ps excitation]**

- **Guide $\bar{H}^+$ ions to free-fall chamber and cool them**
  - **[sympathetic laser-cooling to 10μK ~ 1 neV]**

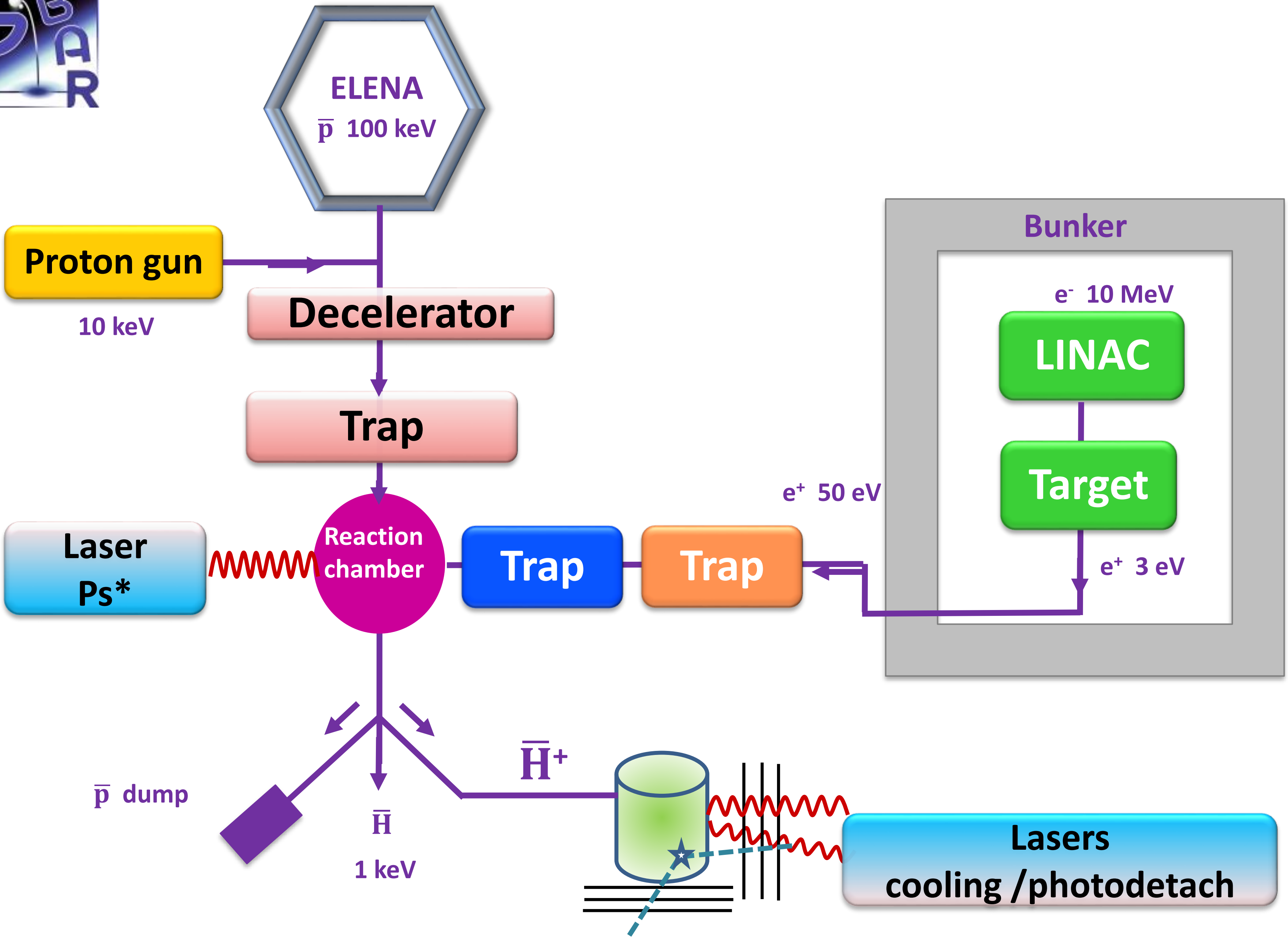
- **Photodetach the excess e^+ : t_0**
  - ***free fall over ~ 20 cm***

- **Detect the $\bar{H}$ atom annihilation**
  [tracking detectors + T-O-F]
  - **location + time**



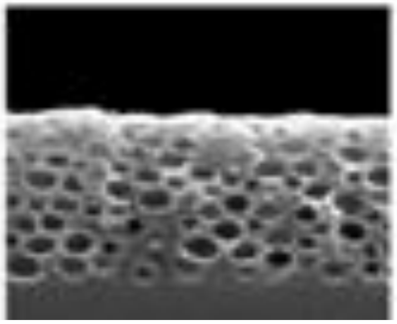
J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561

- **Goal $\Delta g/g \leq 1\%$**


ELENA
$\bar{p}$ 100 keV
Proton gun
10 keV
Decelerator
Trap
Bunker
e^- 10 MeV
LINAC
Target
e^+ 50 eV
e^+ 3 eV
Laser
Ps*
Reaction chamber
Trap
Trap
$\bar{H}^+$
$\bar{p}$ dump
$\bar{H}$
1 keV
Lasers
cooling /photodetach

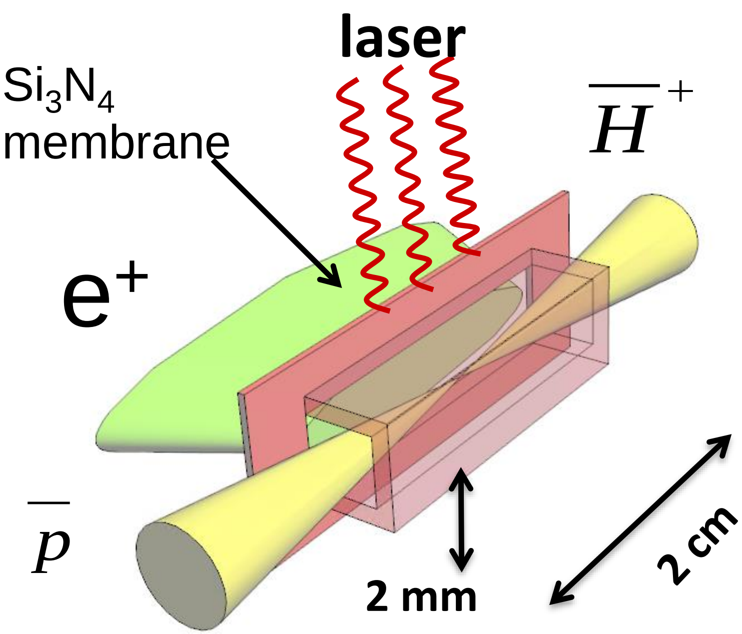
Positronium (Ps) cloud production

- **Create high flux of slow e^+ (few keV)**
  - **9 MeV electron linac => target**
  - **e^+ ‘s moderated by tungsten grid (“moderator”)**

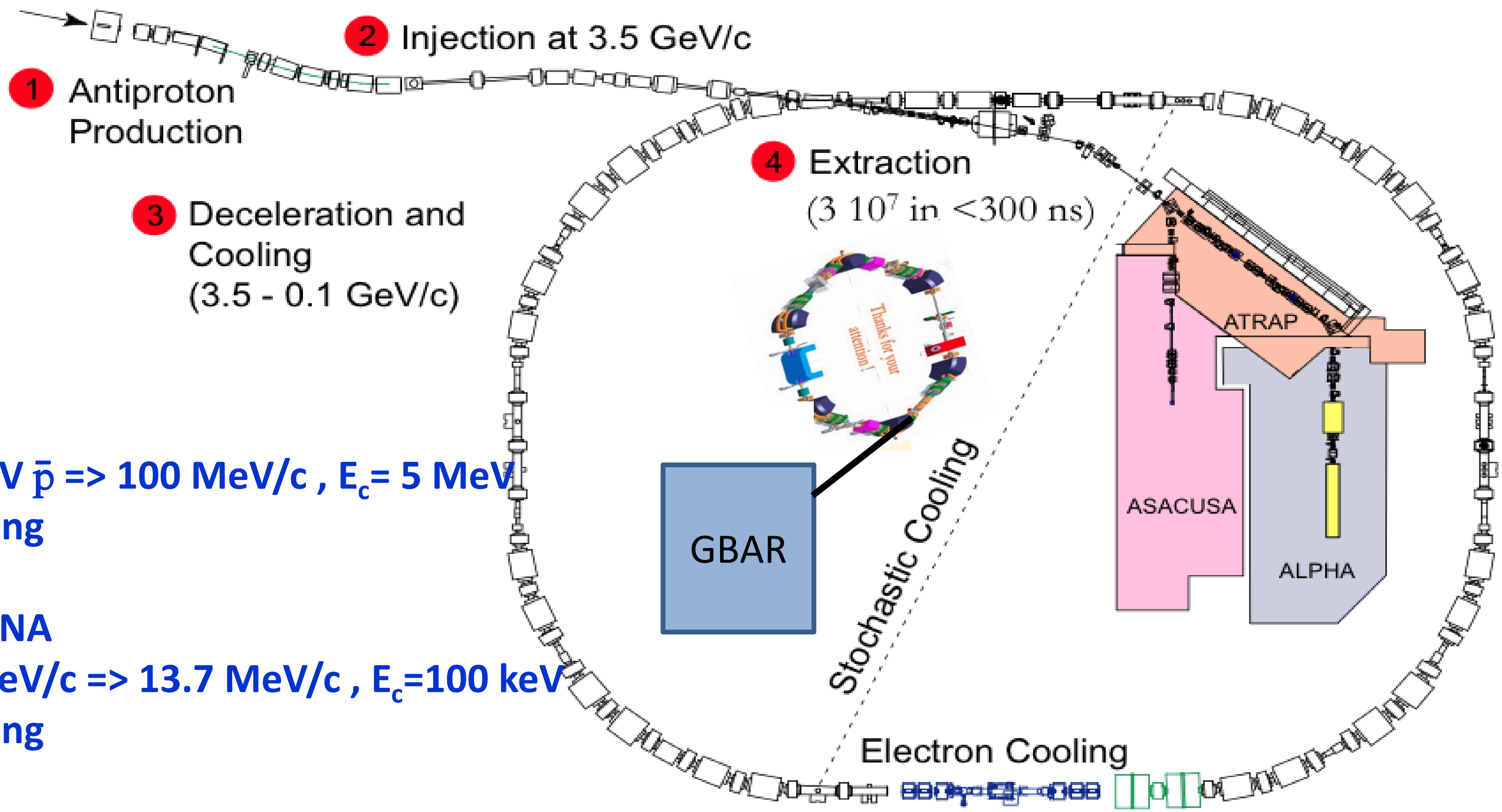


- **Ps production (ortho-Ps : τ= 142 ns)**
  - **pure Silica (SiO_2) with nanometer size pores**
  - **emits Ps upon e^+ implantation, with ~ 30% efficiency**
    - tested and published

- **Ps cloud in reaction tube**
  - **typical size l = 20 mm, diameter 1-2 mm**
  - **Si_3N_4 window for e^+ implantation**
  - **window and mirror for excitation laser**



The ELENA low energy anti-proton ring



- **AD**

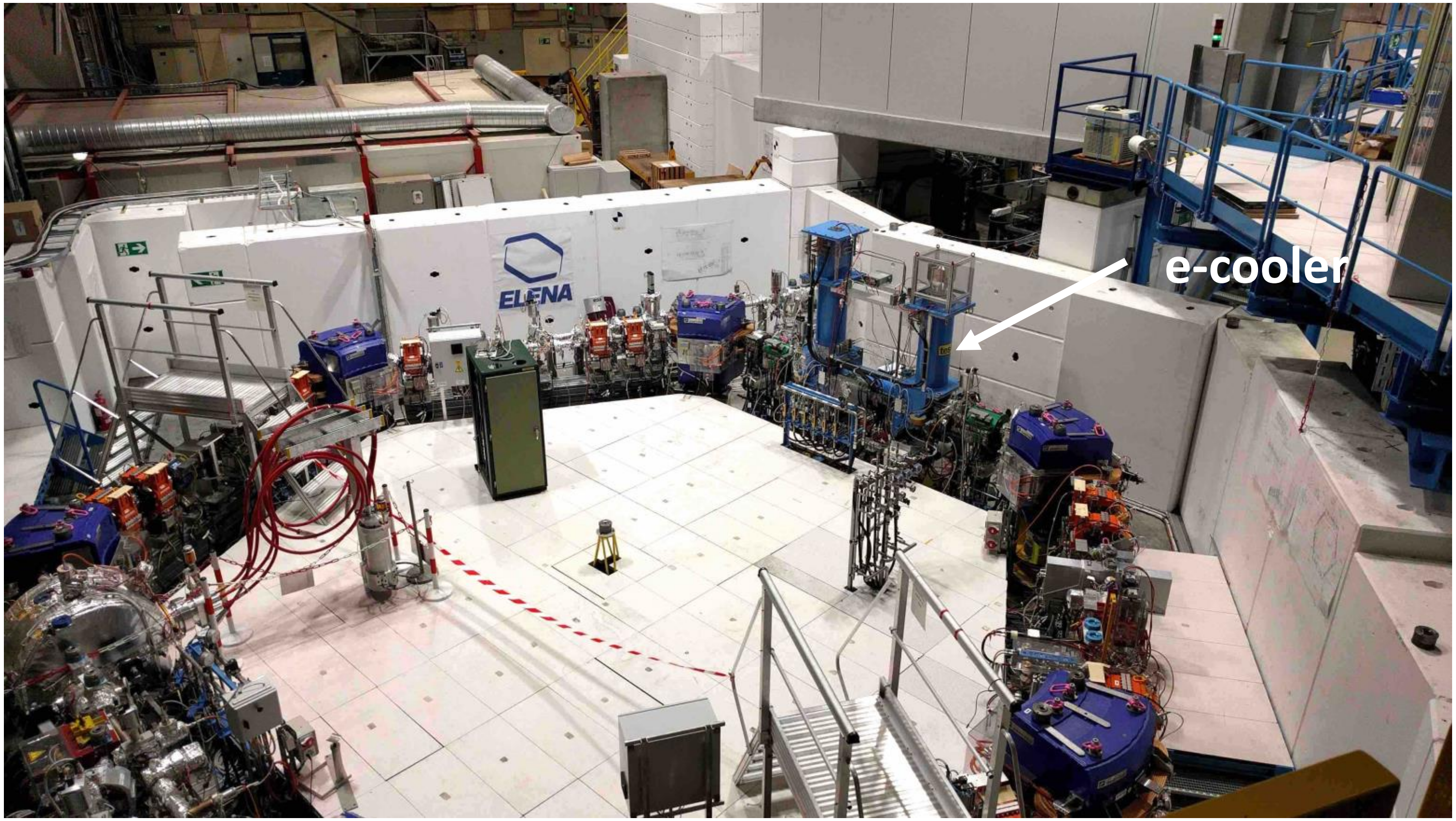
3.5 GeV $\bar{p}$ => 100 MeV/c , E_c= 5 MeV
+ cooling

- **ELENA**

100 MeV/c => 13.7 MeV/c , E_c=100 keV
+ cooling

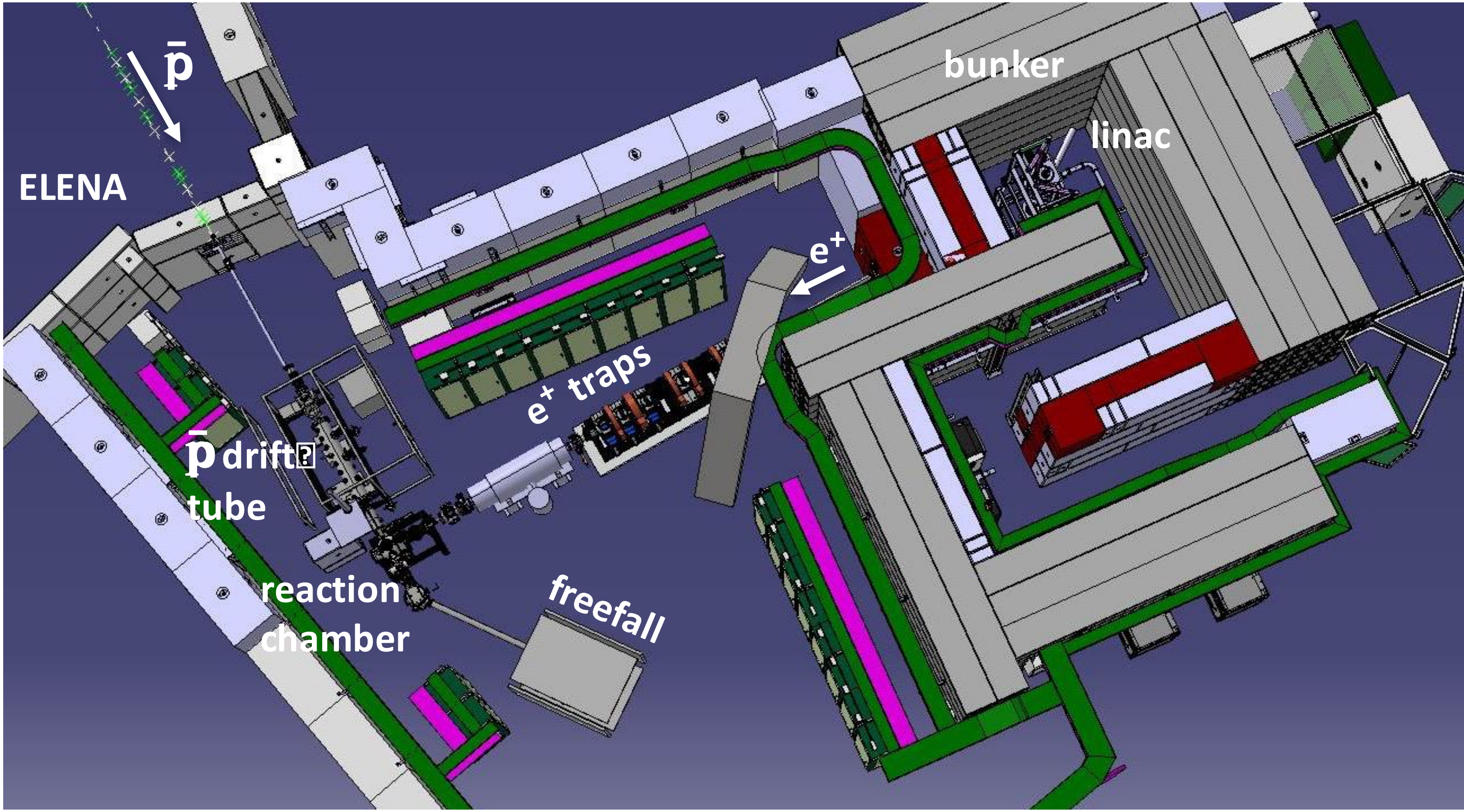
4 bunches (4 expts) every 110 s

ELENA

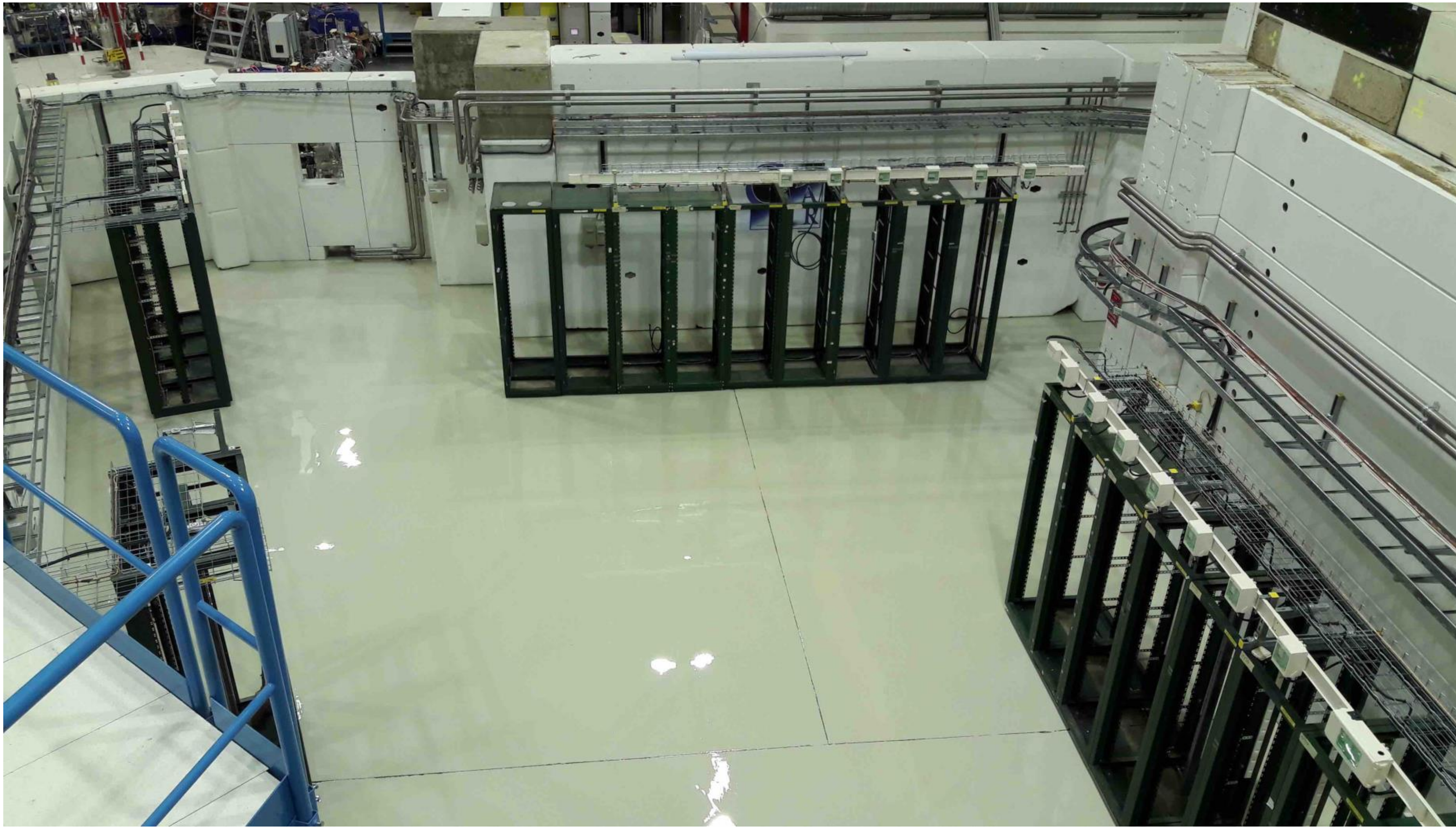


- **Accept 5 MeV pbars from AD, slows and cools them down to 100 keV**
- **Can serve 4 experiments, one $\bar{p}$ bunch (5 10^6) to each, every 110 s**

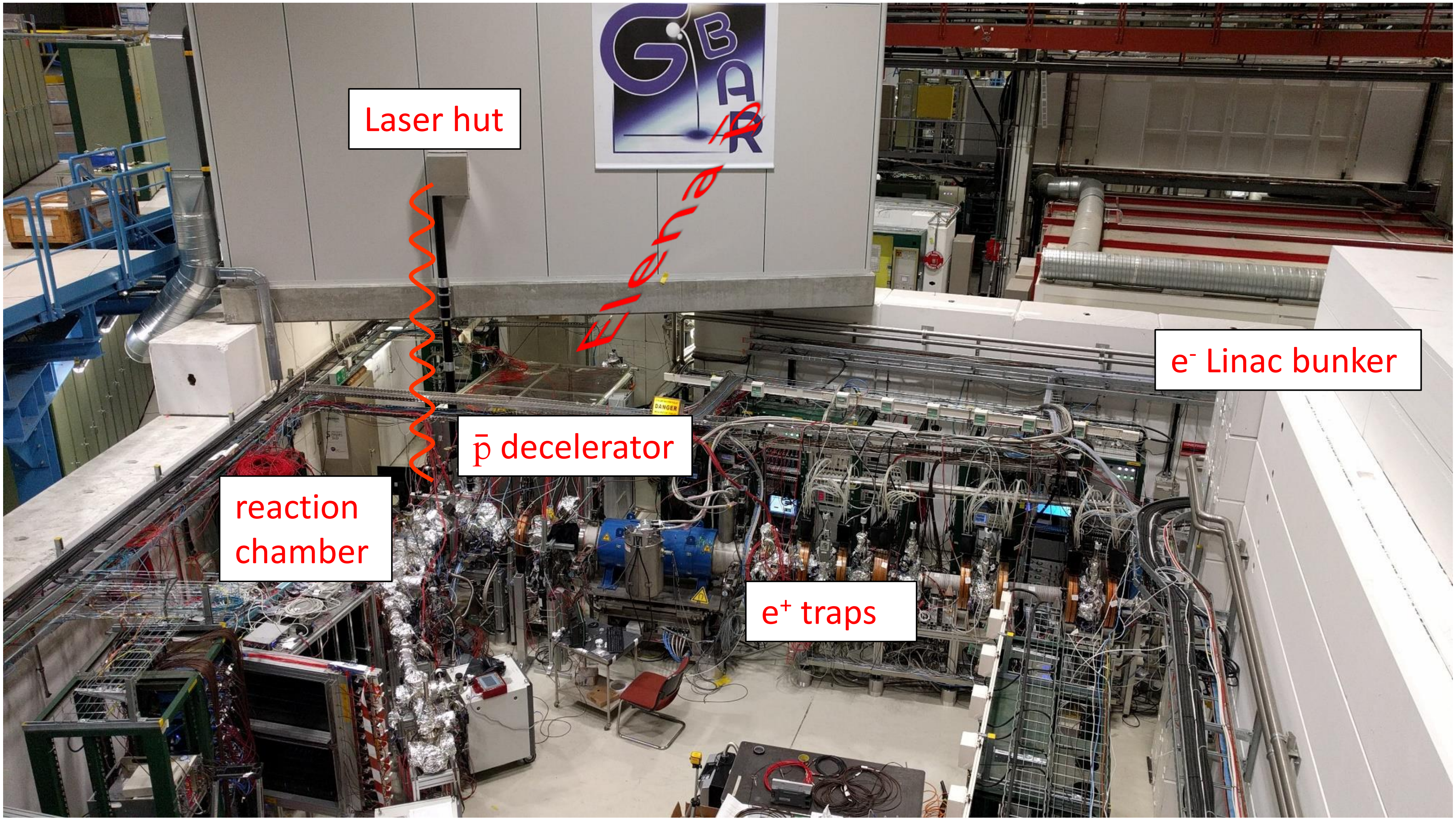
Layout of GBAR in the CERN AD hall



March 2017



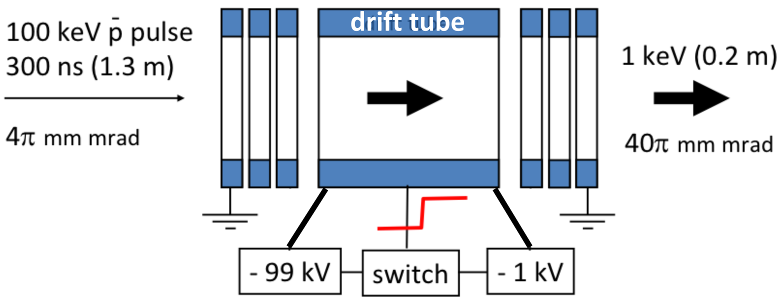
Today



Laser hut
Elena
$\bar{p}$ decelerator
reaction chamber
e^- Linac bunker
e^+ traps

Anti-proton (or proton) drift tube decelerator

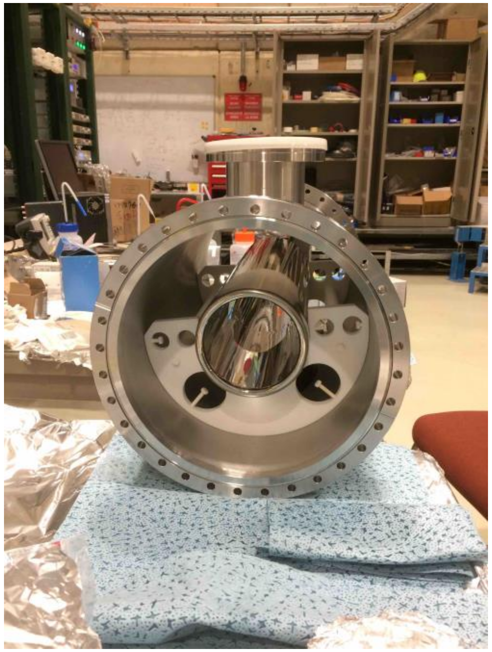
$$100\,\mathrm{keV} \rightarrow 1 - 10\,\mathrm{keV}$$

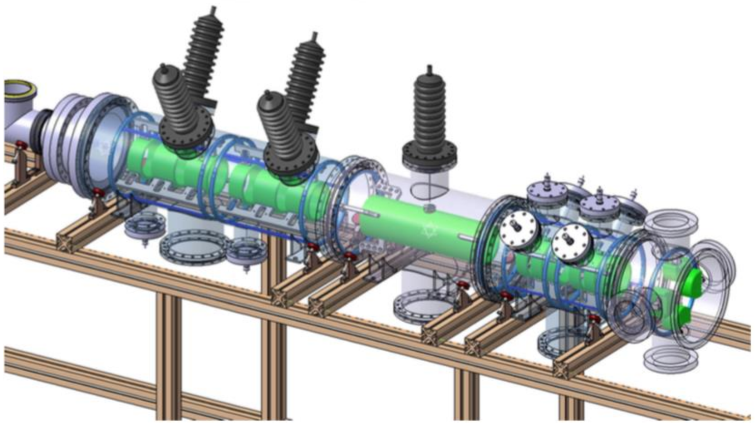


beams from ELENA

$\bar{p}$	every 110 s
H^-	5 s

0





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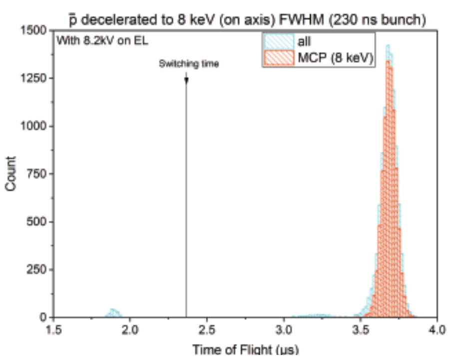
- 100 keV -> 228 ns/m
- 10 keV -> 722 ns/m

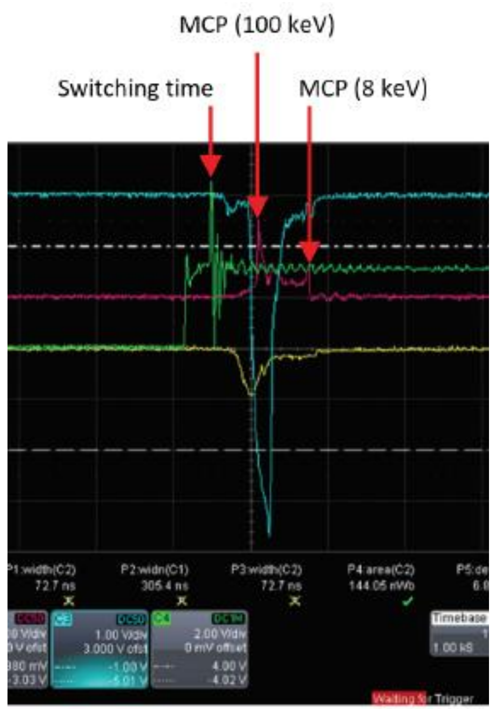
First antiprotons from ELENA

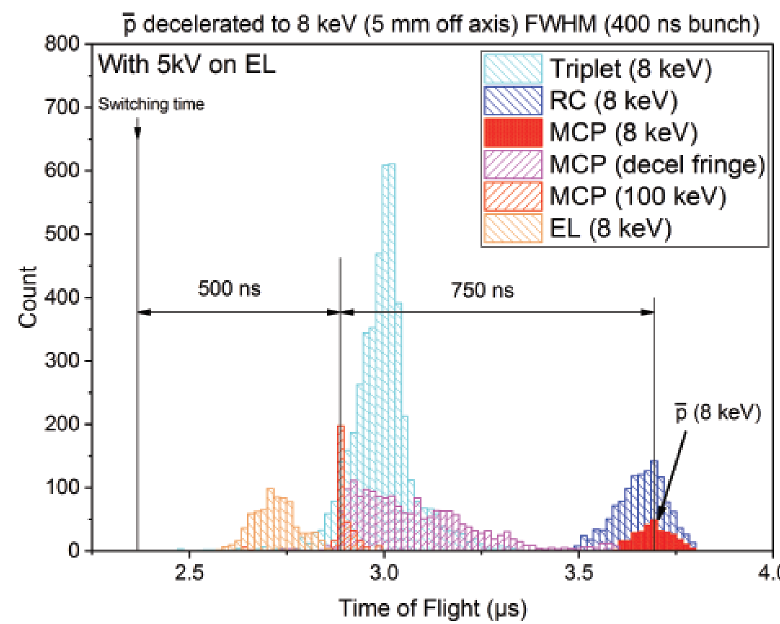
- **In 2018, ELENA delivered p to GBAR from July 20th on.**
  - **Still commissioning ELENA itself**
  - **Beam quality not reaching spec => difficult to use decelerator**
    - bunch length too long (=> drift tube too short…)
    - almost no monitors in our beamline (=> off-centered…)



Ideal situation

Real situation last year =>



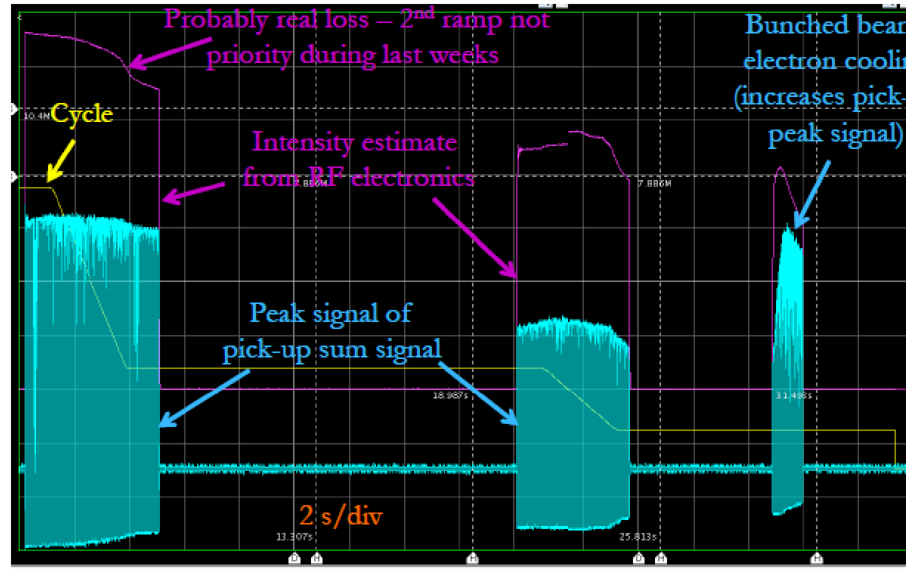


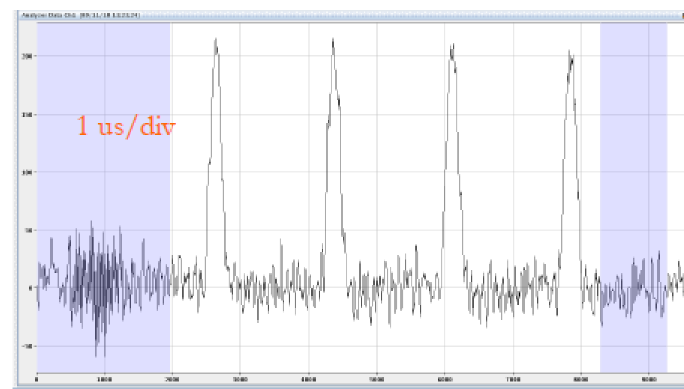
Progress in ELENA

- **Many developments in ELENA**

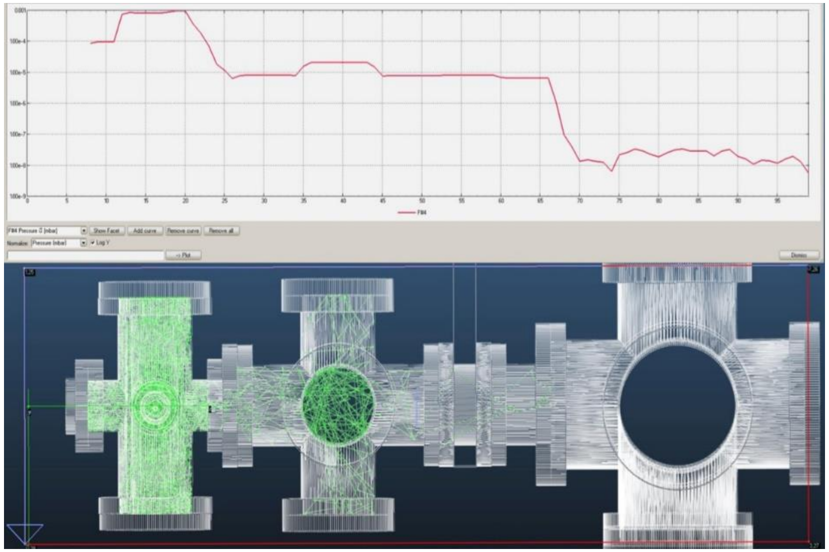
- **On the very last day of operation,**
ELENA almost reached spec parameters
(but still not in our beamline)

  - **2 step deceleration + cooling**
    - 100 MeV/c => 35 MeV/c =>13.5 MeV/c
      5 MeV 610 keV 100 keV
  - **4 bunches, each 0.43 10^7 p**
    (46% overall efficiency)
  - **bunch length FWHM <200 ns**



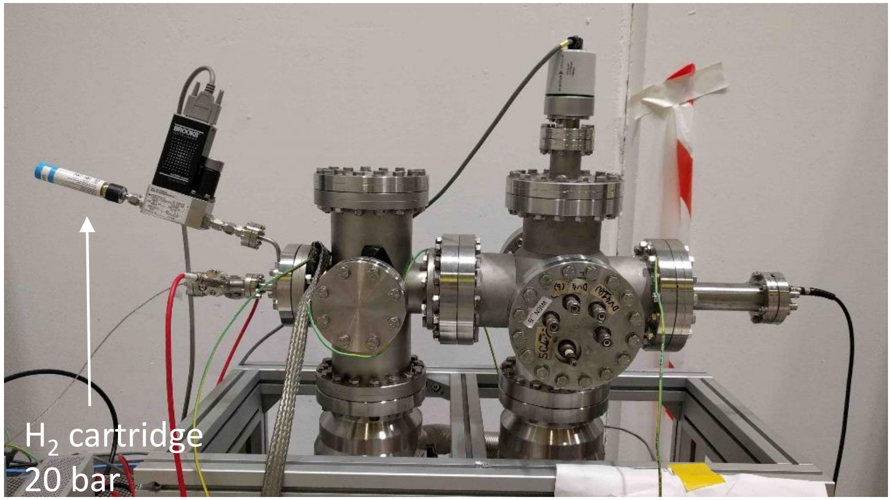


Proton source for developments



pumping & restrictions → 10^{-8} mbar

Test bench



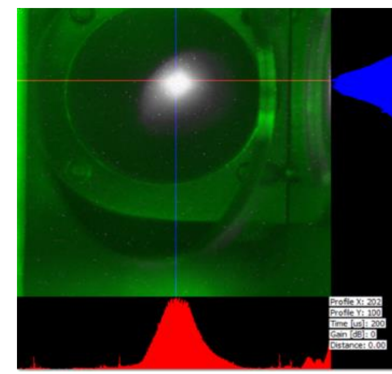
Antiproton trap

- **7 T superconducting magnet with active shielding (Korea University Seoul) operated at 3 T in GBAR**
- **being equipped as a trap**
- **ship to CERN in 2019**

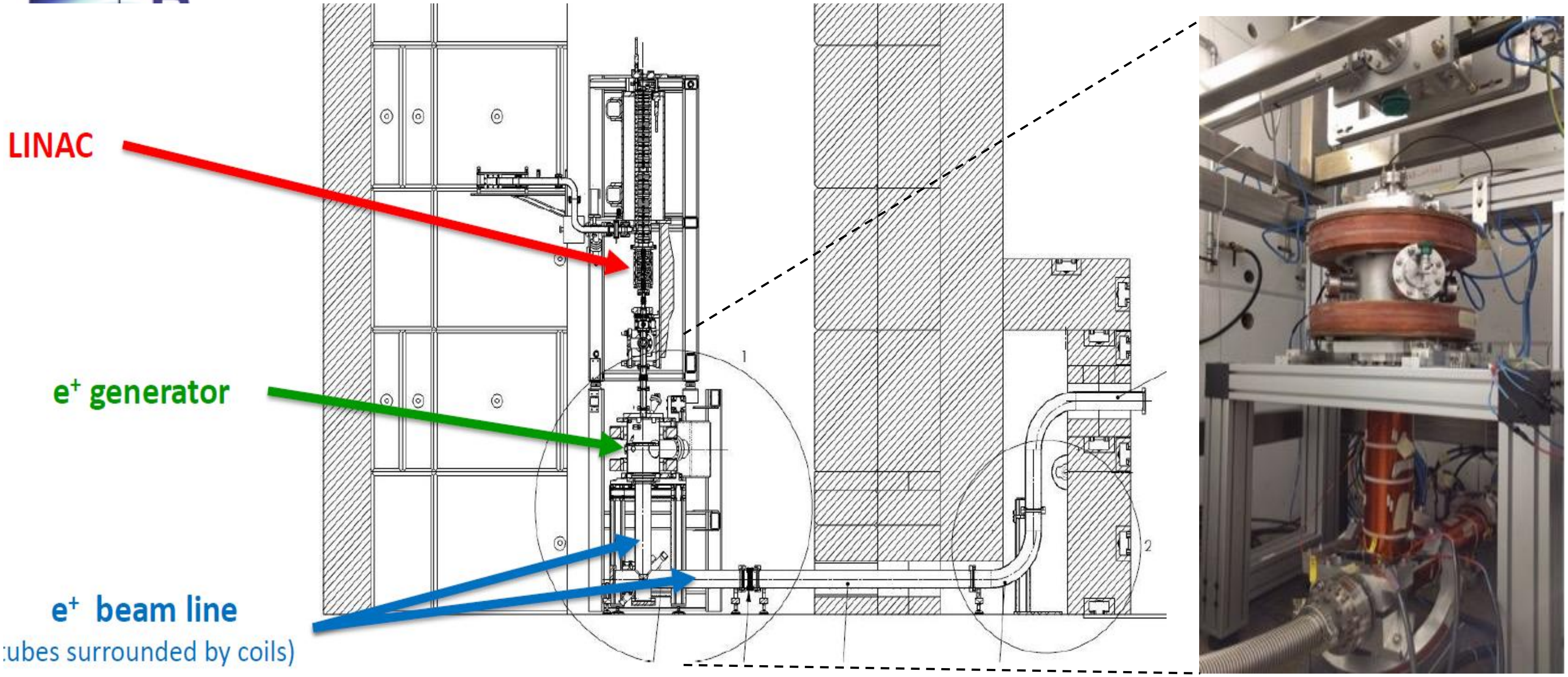
Electron LINAC

- **9-10 MeV**

- **nominal 300 Hz 4.2μs pulses**
  100 mA current in pulse
  (0.2 mA average)

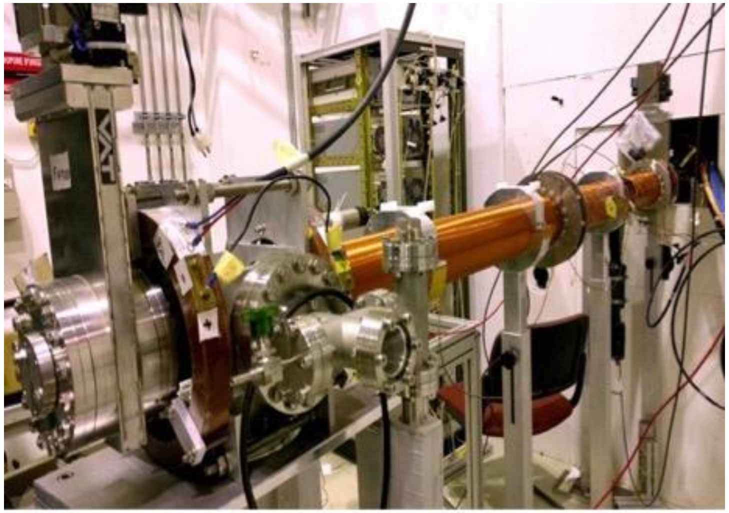


Positron production

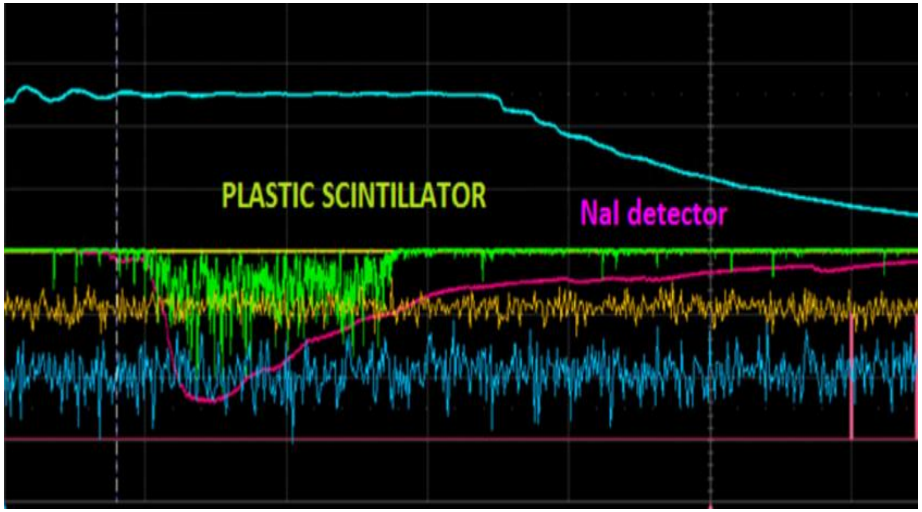


- **Water-cooled Tungsten target** ***1Mrad every 5h !***
- **Tungsten mesh moderator**
- **8 mT solenoids guide the slow (~3eV) e^+ out of bunker**

Positron production measurements



e^+ beam line exiting the bunker



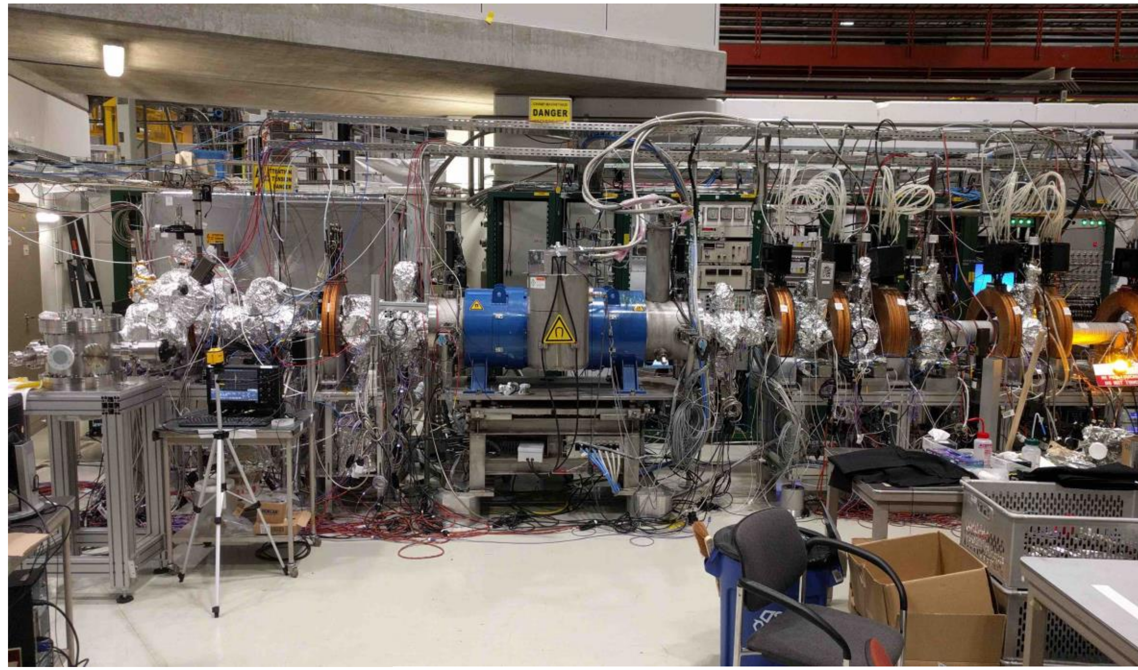
first e^+ signals on Nov. 17

- **e^+ yield outside the bunker measured by annihilation γ's**
  - **energy measured by potential grid: 1.3 eV RMS (OK for trapping in buffer-gas trap)**
  - **demonstrated ~ 3 10^5 e^+ /pulse**
  - **expect ~ 7 10^7 e^+ /second at 300 Hz with present setup. Aim for 3 10^8 e^+ /second**

Positron traps

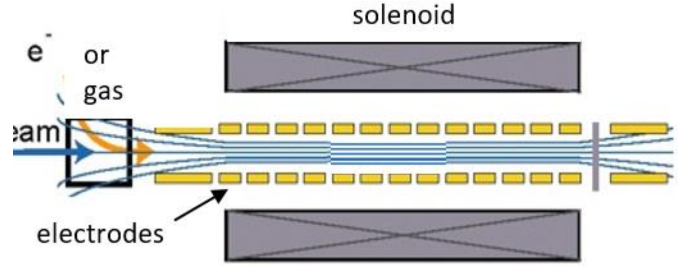
- trap 1: buffer gas

trapping and cooling (N_2/CO_2)
commissioning
Trapping efficiency ~ 5%
Goal 25%



- trap 2: High mag field (5T)

accumulation in UHV
and e^- cooling
Just starting operation,
Already stored 10^8 e^+ with
long lifetime



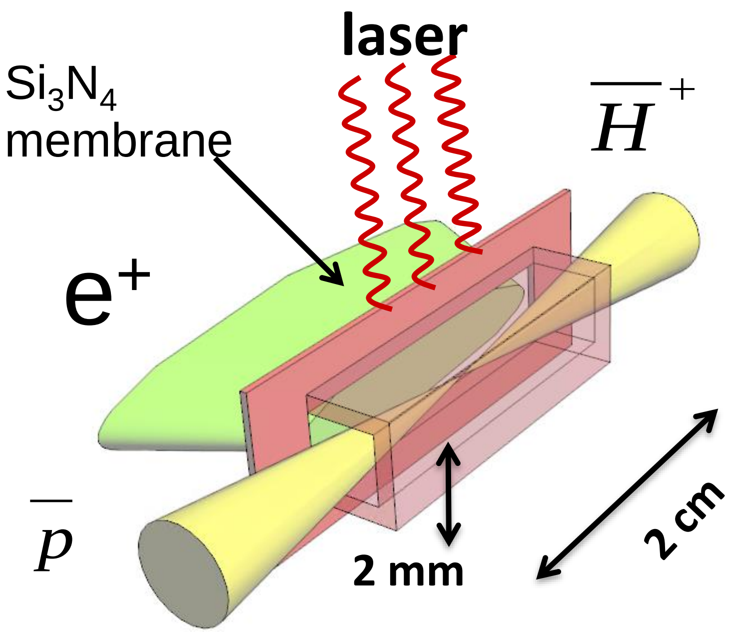
cylindrical Penning-Malmberg trap

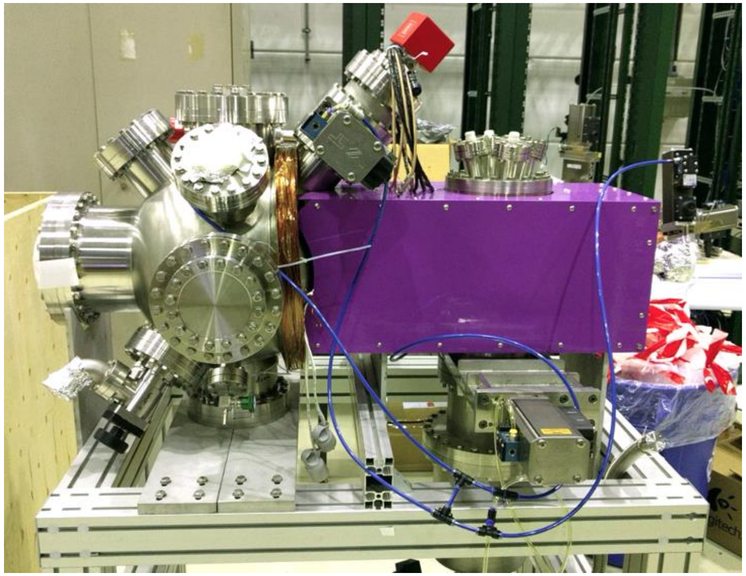
- Goal: accumulate 3 x 10^{10} e^+ in 110 s

Reaction chamber

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

$$p + Ps \rightarrow H + e^+$$
$$H + Ps \rightarrow H^- + e^+$$

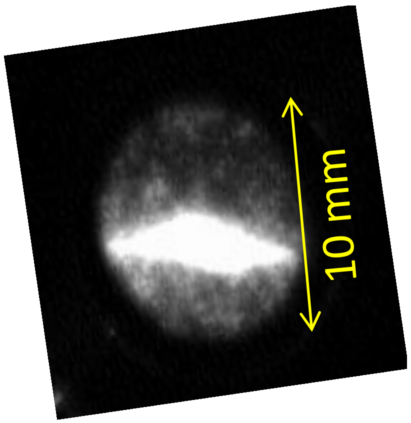




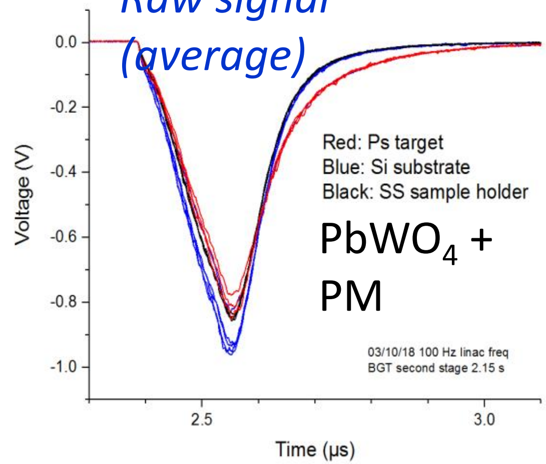
reaction chamber

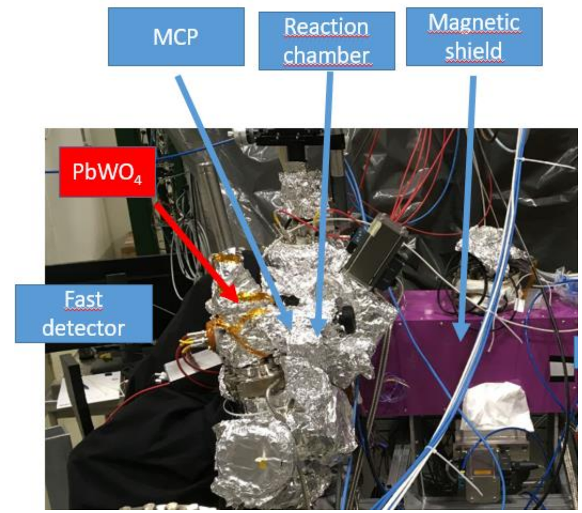
Ortho-Positronium produced at GBAR

Positron trapped in buffer gas ejected on the target

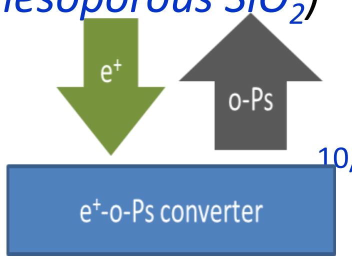


Raw signal (average)





Positron-positronium converter (mesoporous SiO_2)



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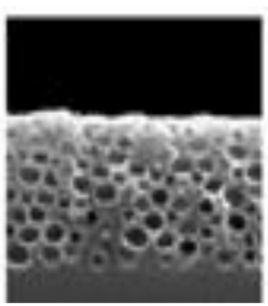
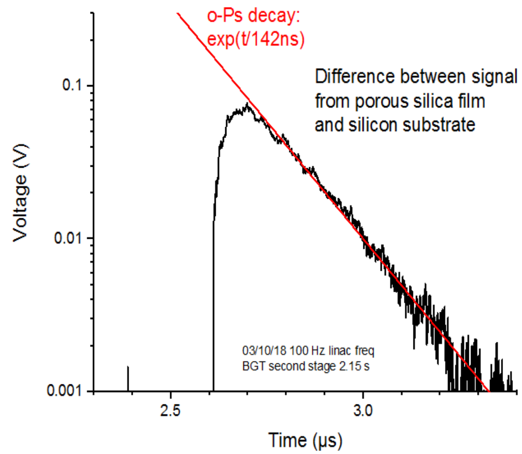




Differential signal showing oPs lifetime

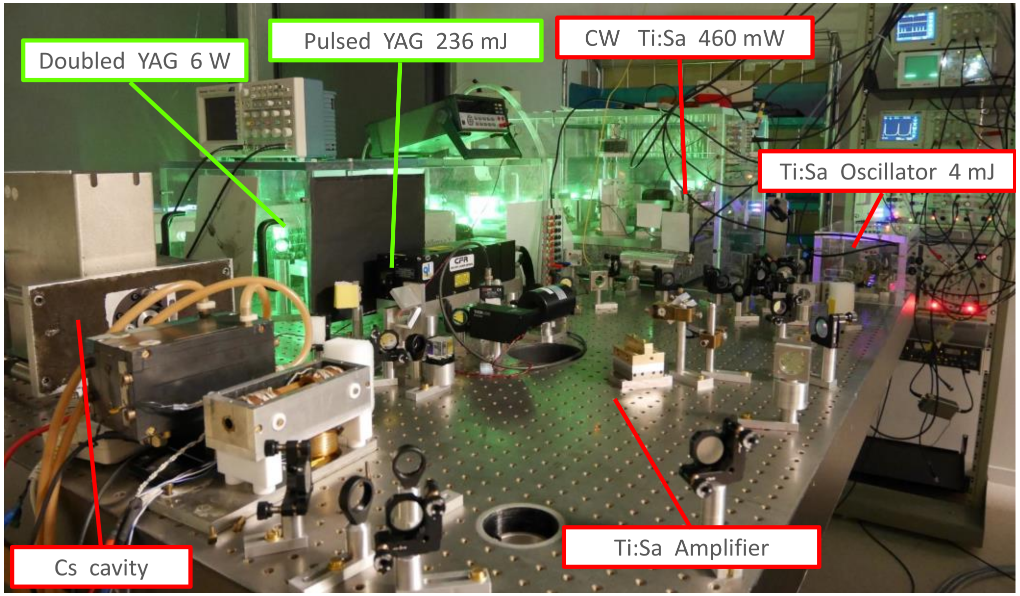
Ps excitation laser

- Laser prepared at LKB (Paris)

- Now installed in GBAR, starts commissioning

- CW TiSa seeder

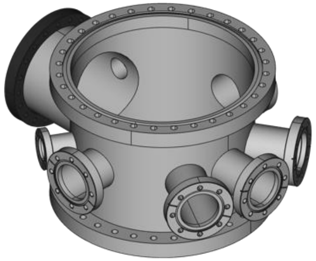
and oscillator cavity
5 mJ @ 820 nm
after ampli 26 mJ
Goal 10 mJ @ 410 nm

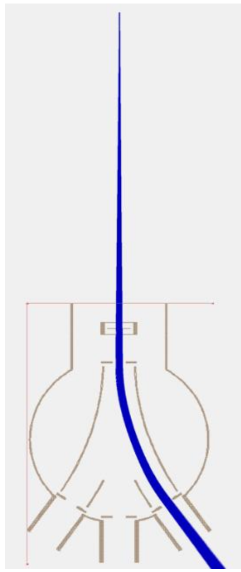


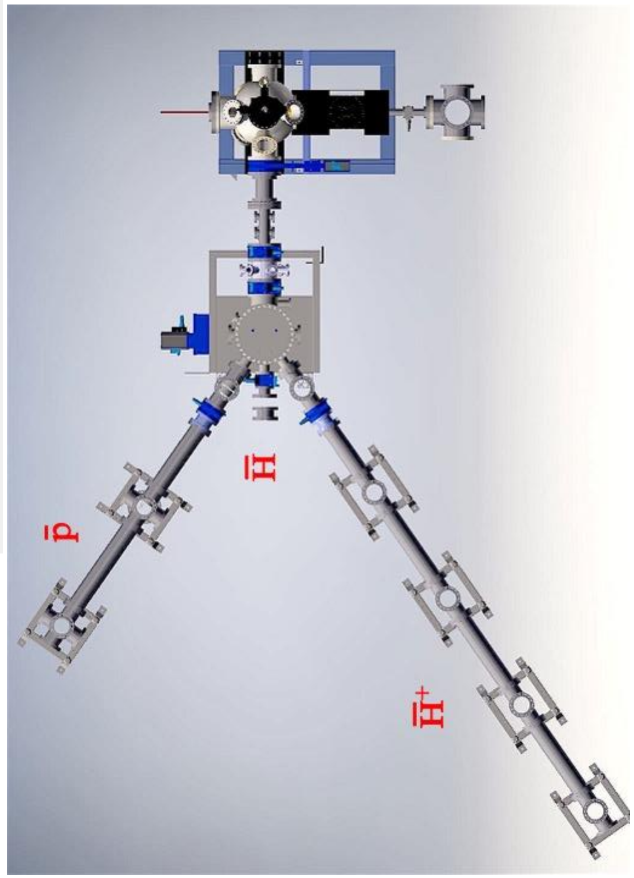
2 photon (410 nm) transition
Ps 1S-3D
=> increase
cross-sections

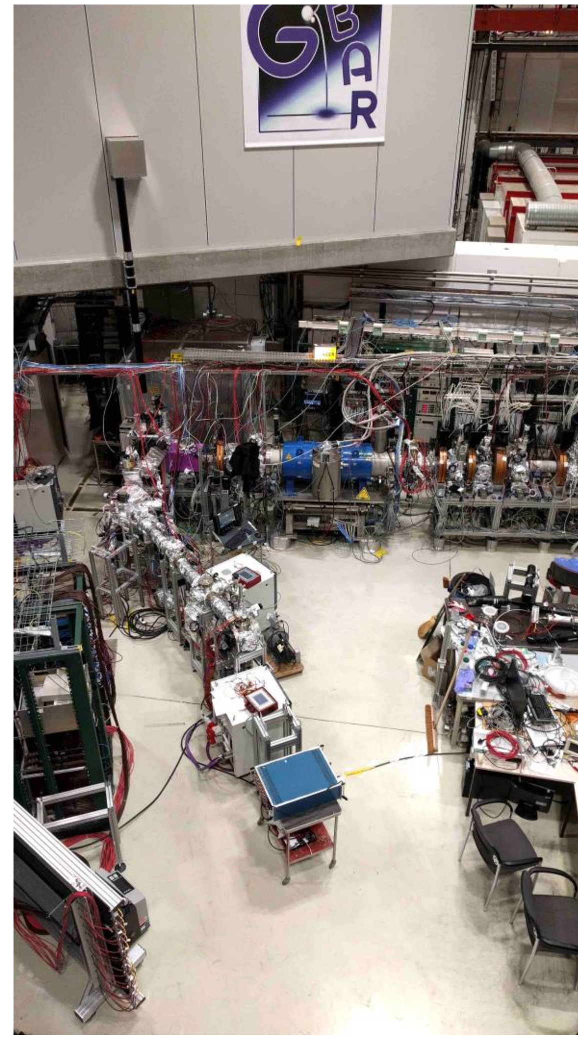
inside the
reaction chamber:
target holder
and laser mirrors

Ion separation and transport







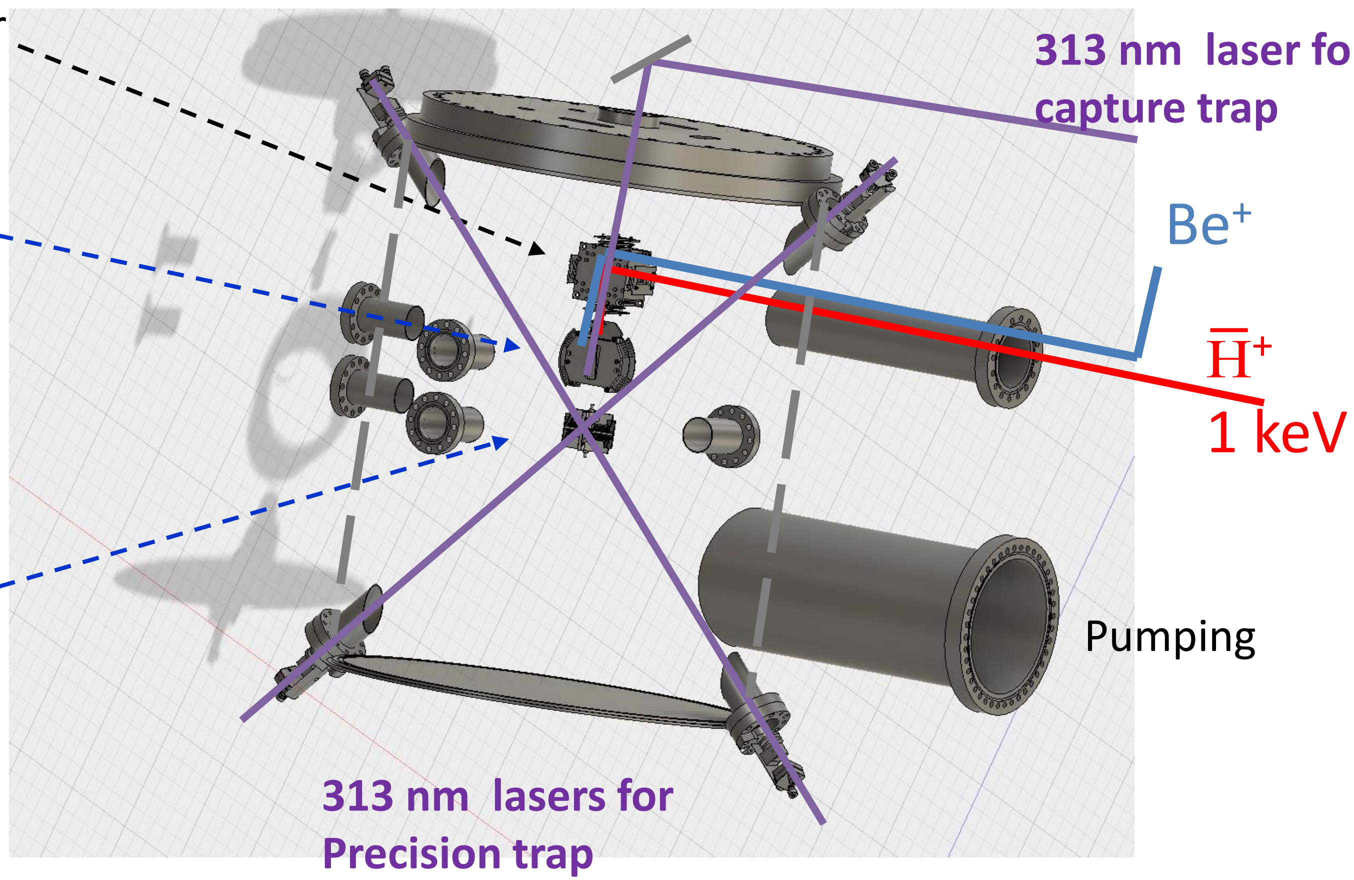


Cooling of the $\bar{H}^+$ ion

Free-fall chamber: ϕ = 50 cm, h= 60 cm

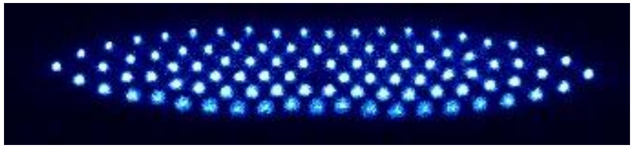
Paul trap
Stores Be^+ ions
in quasi-crystal
100 neV, T ~ 10mK
cools $\bar{H}^+$ by collisions

Precision trap
1 Be^+ ion
+ $\bar{H}^+$
Raman sideband cooling
1 neV, T = 10 μK
V ~ 1 m/s

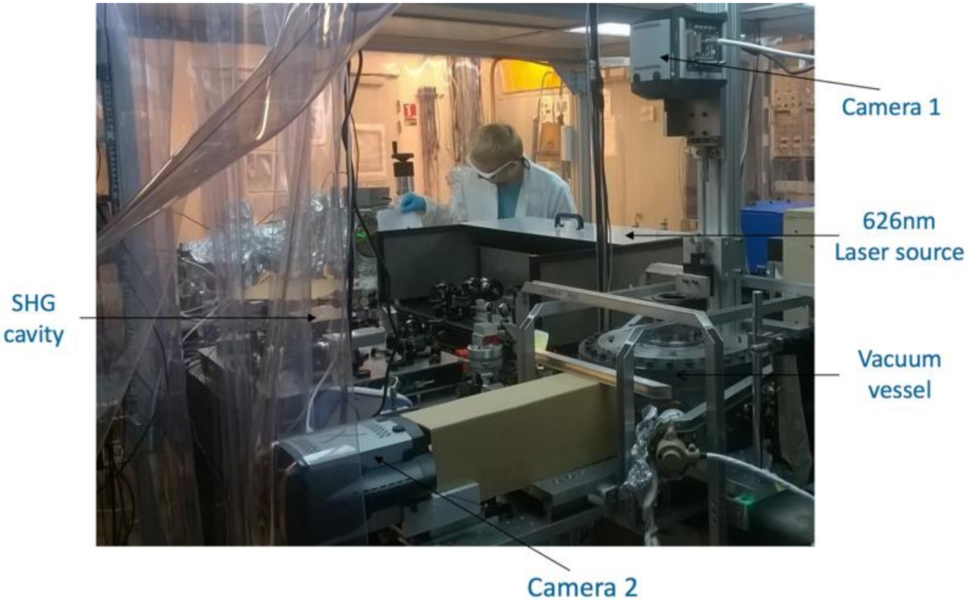


cooling of the $\overline{H}^+$ ion (LKB-Paris, Mainz)

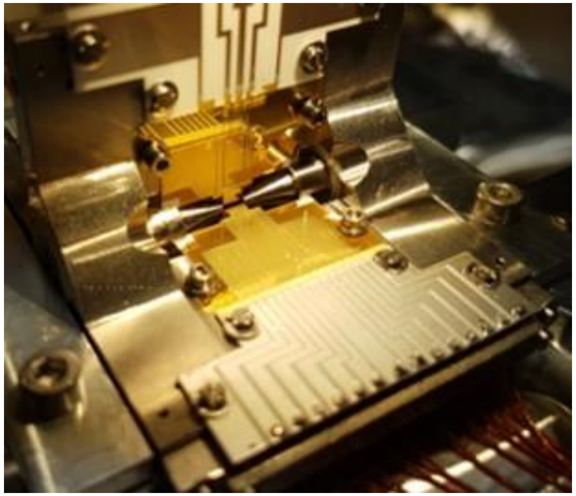
- **Capture (Paul) trap**
  - Cooled Be^+ ions



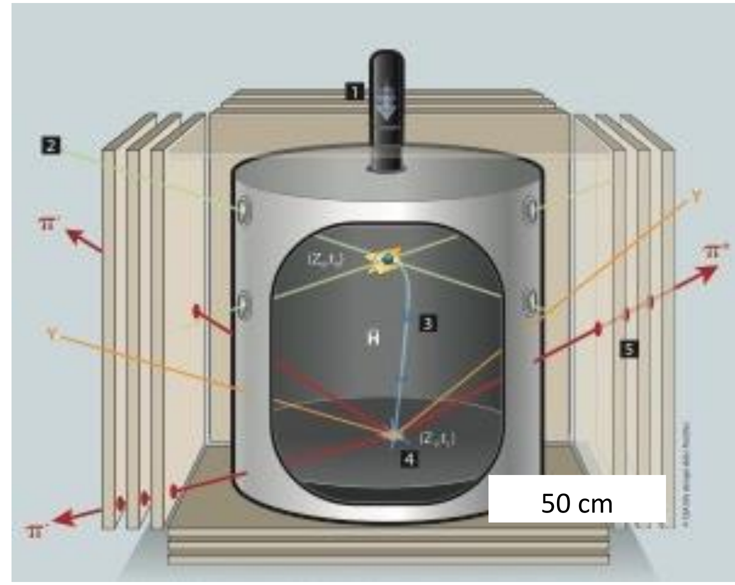
  - dark spot: H_2^+ or H_3^+
  - may need a second ion type (HD^+ ?)



- **Precision cooling trap**
  - 1 Be^+ ion + $\overline{H}^+$
  - Raman sideband cooling



Free-fall chamber and detection



Free fall chamber :

h = 60 cm (20 cm fall), Ø 50 cm

- **Inner cooling traps**
  - capture trap (Be crystal)
  - precision trap (Raman sideband)
- **Photodetachment laser 1.64 μ**

- **track detectors**
  - MicroMegas detectors (6 triplets of 50cmx50cm)
- **Time-of-Flight counters (4 large walls)**
  - First plane operational in Gbar area

Status and Outlook

All CERN accelerators stopped end of 2018 for 2 years ("LS2") : no $\bar{p}$ until 2021!

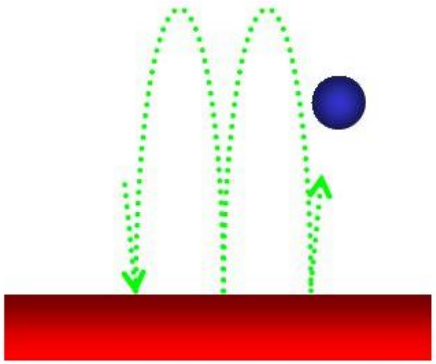
- **During LS2**
  - **Optimize the e^+ line: LINAC, traps, Ps, Ps-laser…**
  - **Improve the $\bar{p}$ line**
    - **With protons from proton source**
    - **Continue commissioning of ELENA and beamline with H^-**
  - **Mimic physics with protons: reactions 1 and 2, make hydrogen and H^- ?**
      - Ps excitation
  - **Finalize and implement free-fall chamber and cooling lasers**

- **In 2021**
  - **Finish commissioning of ELENA and beamline with $\bar{p}$**
  - **Measure $\bar{H}$, then $\bar{H}^+$ production**
  - **Commission $\bar{H}^+$ transport and cooling**
  - **Commission photodetachment laser**
  - **Free-fall !**

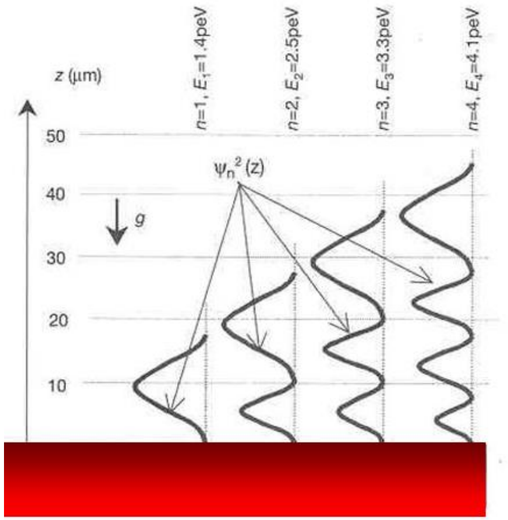
Further future

- **If all the above works…**

Measurement of gravity on ultra-cold neutrons by bouncing + interference (Nesvizhevsky, ILL)



Neutron above a mirror in the Earth's gravitational field



- **Some surfaces should be reflectors for $\bar{H}$ (Si, SiO_2, liquid He…)**

=> could allow measurement of g($\bar{H}$) to very high precision (10^{-4} ?)

https://arxiv.org/abs/1409.0705

Thank you!

Merci!

Additional slides

The GBAR Collaboration

D. Banerjee, F. Biraben, M. Charlton, M. Chung, P. Cladé, P. Comini, P.-P. Crépin, P. Crivelli, O. Dalkarov, P. Debu, L. Dodd, A. Douillet, G. Dufour, P. Dupré, P. Froelich, S. Guellati, R. Guérout, J. M. Heinrich, P.-A. Hervieux, L. Hilico, A. Husson, J. Hwang, P. Indelicato, G. Janka, S. Jonsell, J.-P. Karr, K. Khabarova, B.H. Kim, S.K. Kim, Y. Kim, E. Kim, N. Kolachevsky, N. Kuroda, A. Lambrecht, B. Latacz, A. Lee, J. Lee, A.M.M. Leite, K. Lévêque, L. Liszkay, P. Lotrus, T. Louvradoux, D. Lunney, N. Madsen, G. Manfredi, B. Mansoulié, Y. Matsuda, A. Mohri, G. Mornacchi, V. Nesvizhevsky, F. Nez, K. Park, P. Pérez, B. Radics, C. Regenfus, J.-M. Rey, J.-M. Reymond, S. Reynaud, J-Y Roussé, A. Rubbia, J. Rzadkiewicz, Y. Sacquin, F. Schmidt-Kaler,N. Sillitoe, M. Staszczak, H. Torii, B. Vallage, M. Valdes, D.P. van der Werf ,A. Voronin, S. Wolf, S. Wronka, Y. Yamazaki

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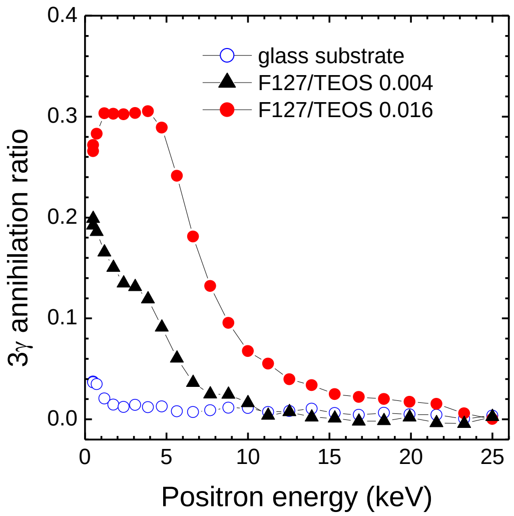
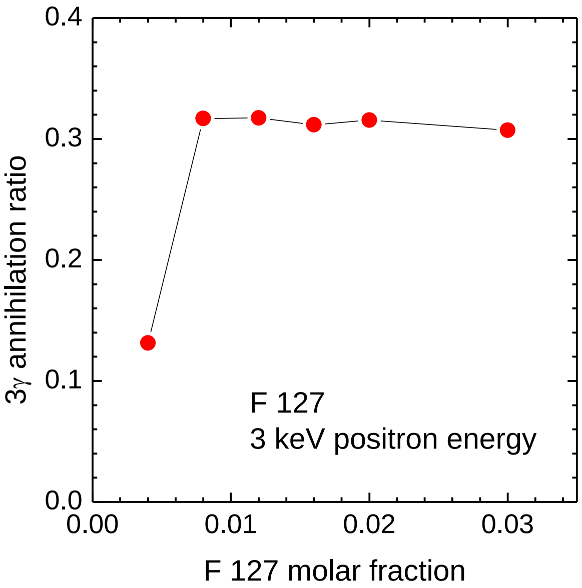
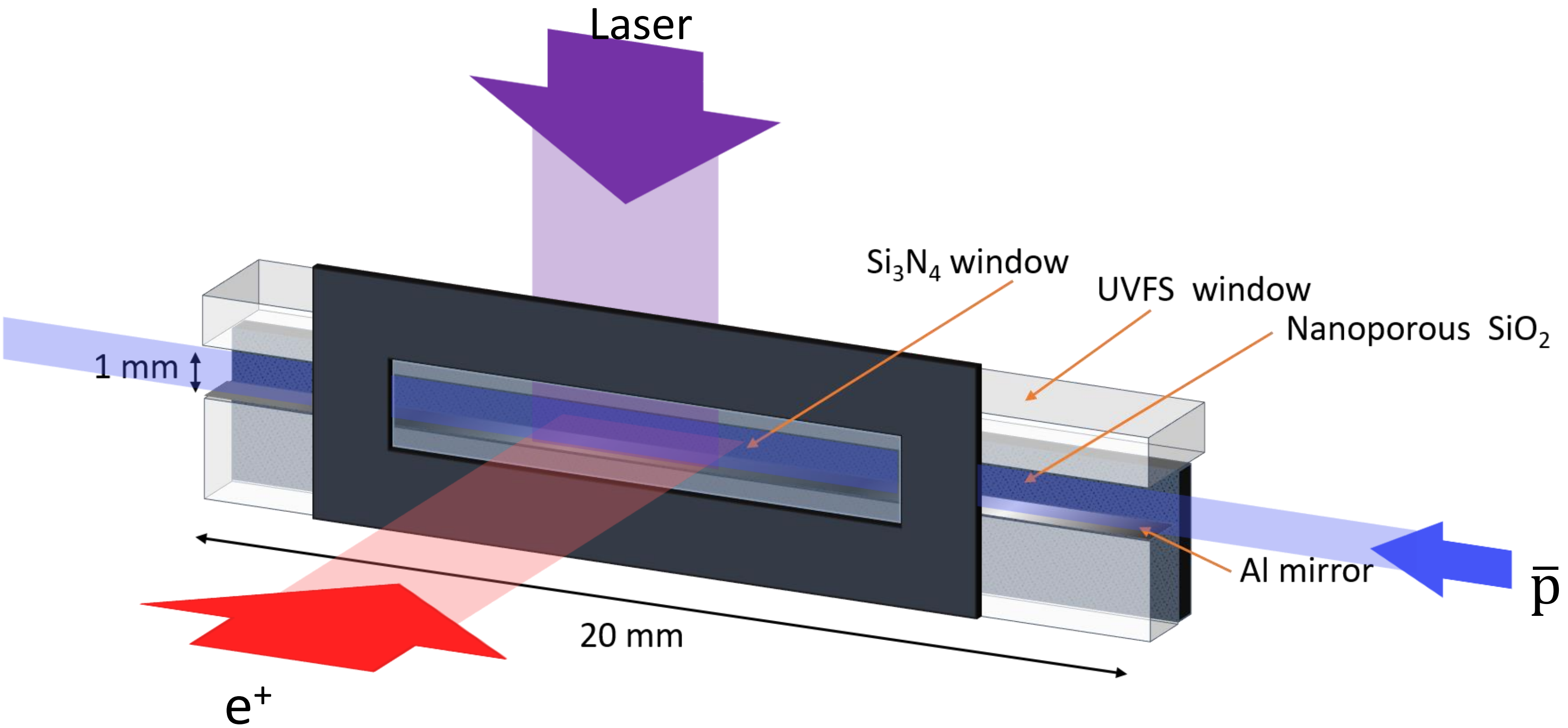
Ps production in SiO_2

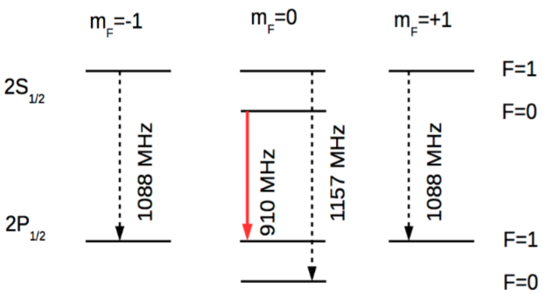


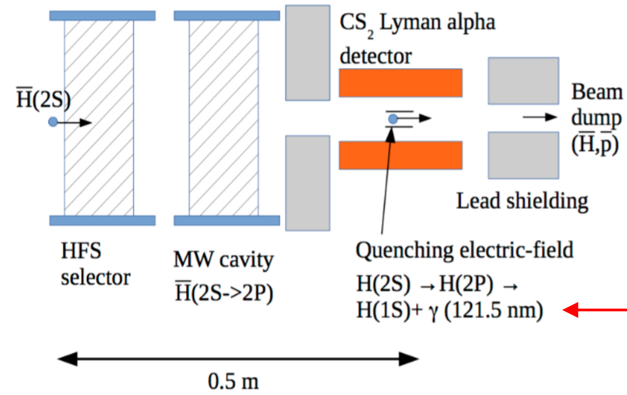


Reaction chamber



$\bar{\mathrm{H}}$ Lamb shift





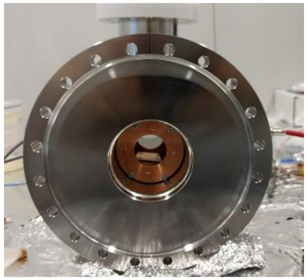
detect those γs

Measure quenched fraction as a function of microwave frequency

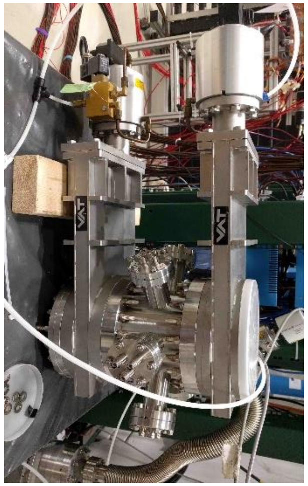
4 months data → 100 ppm on line center

$$\Delta E = \frac{1}{12}\alpha^4 m_r^3 r_p^2$$

→ 10% on $\bar{\mathrm{p}}$ radius

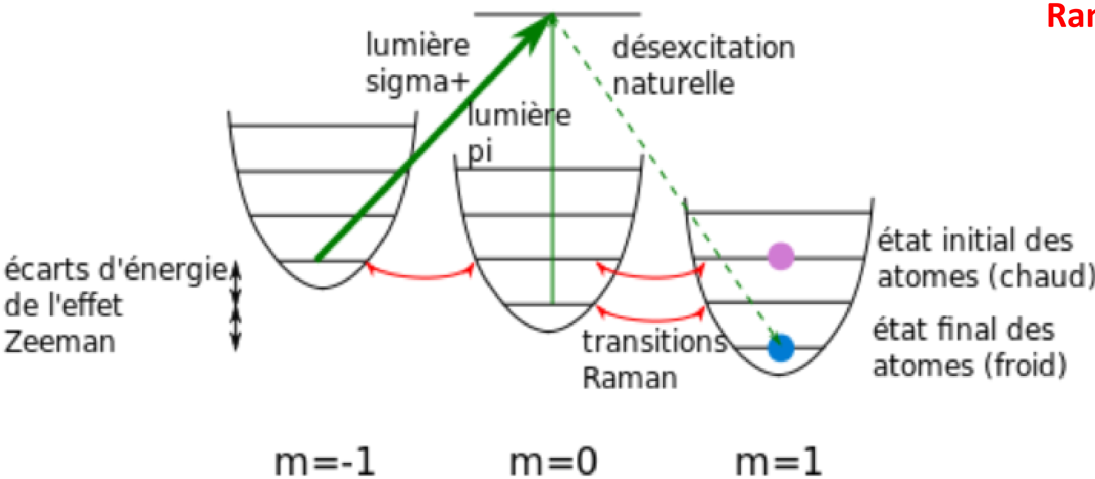


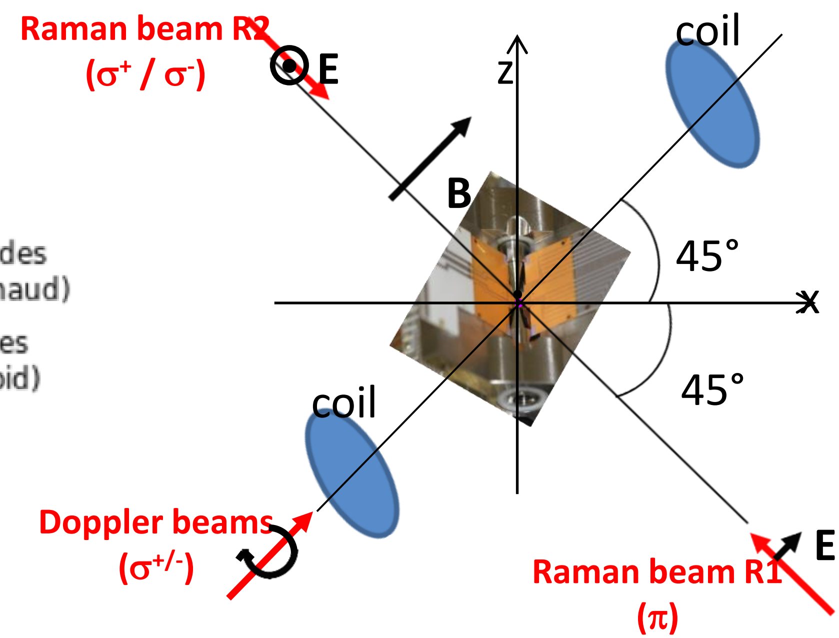
microwave cavity



CS_2 coated MCPs

Raman sideband cooling





Beam arrangement 0: $\mathbf{k}_1 - \mathbf{k}_2 = k\left(\mathbf{e}_x + \mathbf{e}_y + 1.41\mathbf{e}_z\right)$