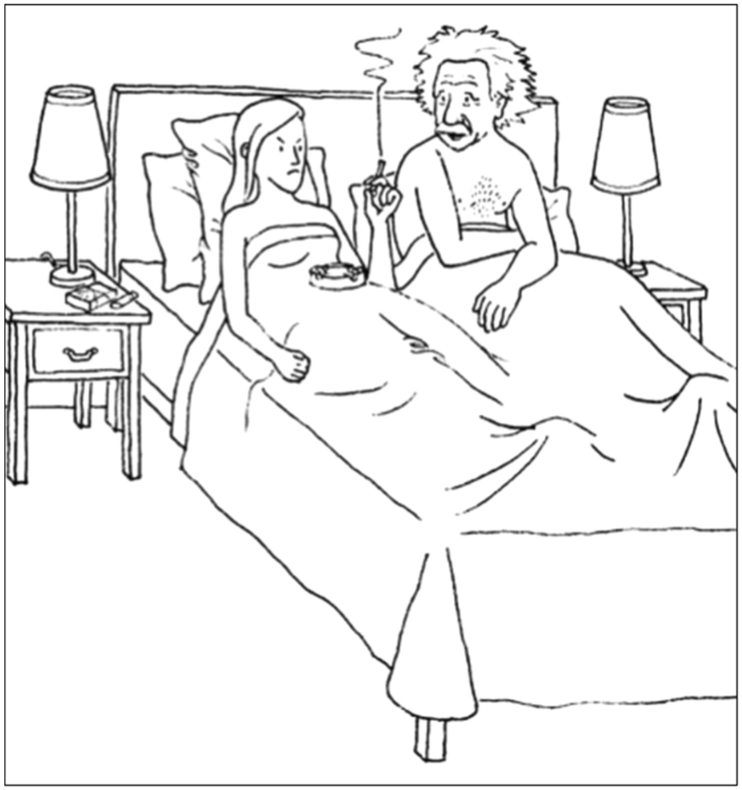
Gravitational Behavior of Antimatter at Rest

David Lunney (for the AD-7/GBAR Collaboration)

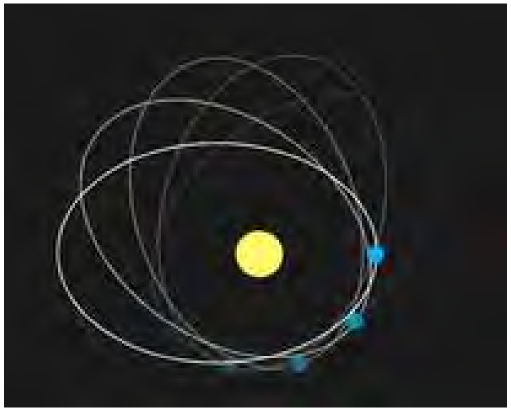
CSNSM (IN2P3-CNRS) Université de Paris Sud, Orsay

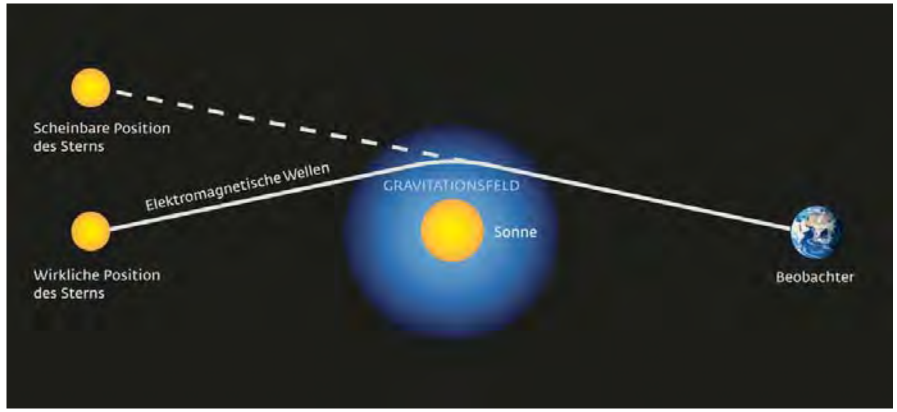
"Nothing yet – how about you, Newton?"
-Gary Larson, The Far Side

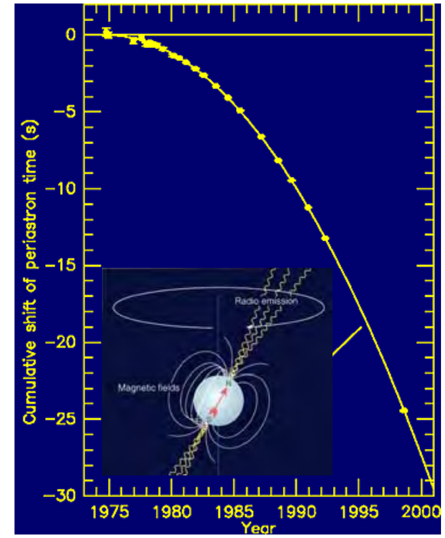


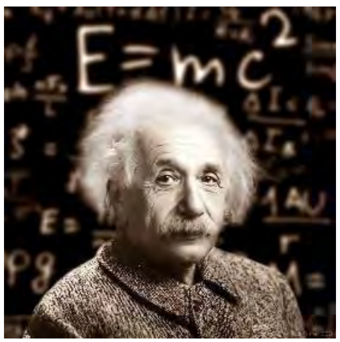
"To you it was fast."
-Eric Lewis, The New Yorker

Einstein: General Relativity

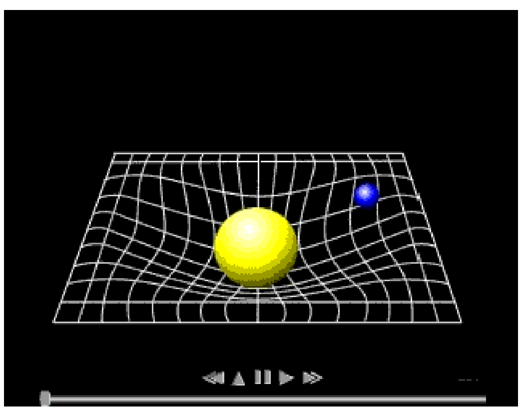


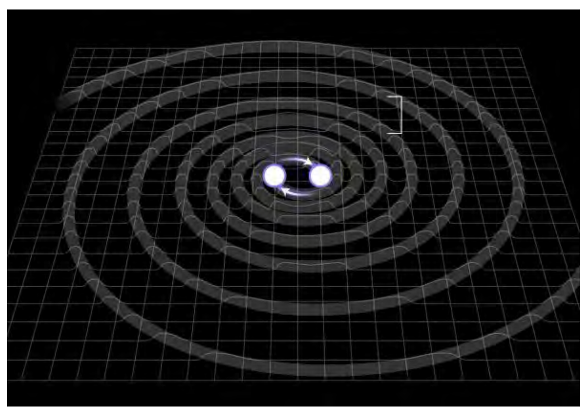




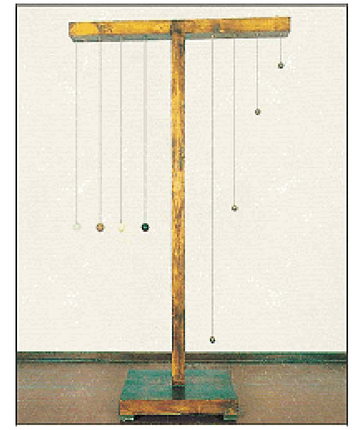


1907: equivalence principle of falling bodies
1915: theory of GR published (Mercury's perihelion)
1919: Dyson, Eddington & Davidson: solar eclipse
1974: Taylor-Hulse pulsar (Nobel prize in 1993)
2015: Gravitational waves
2019: First image of Black Hole





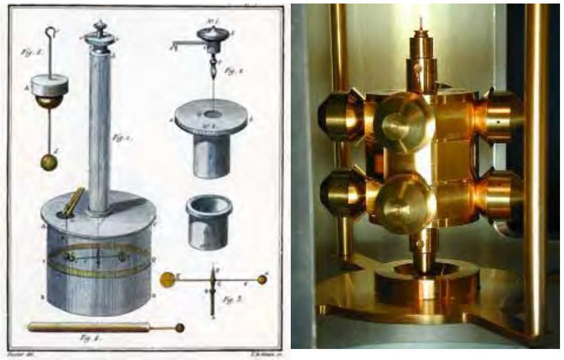
Relativity: the equivalence principle



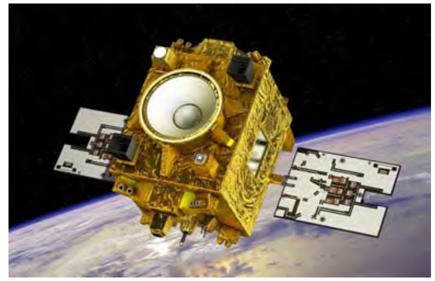
$m_{\text{gravity}} = m_{\text{inertia}}$

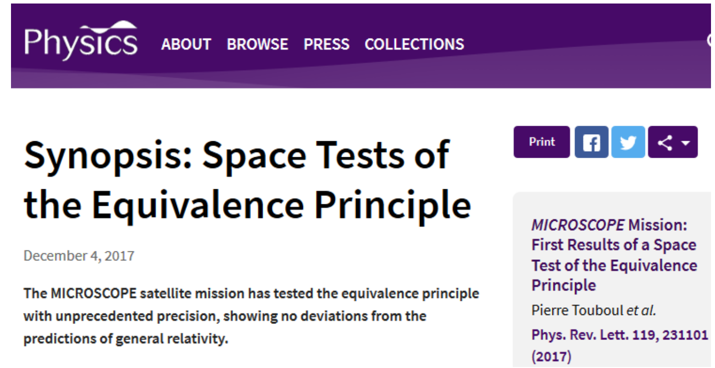
Early EP experiments

Testing the equivalence principle



Coulomb → Eötvös → Eöt-Wash (Seattle)
T.A. Wagner, S. Schlamminger, J.H. Gundlach & E.G. Adelberger, *Class. Quantum Grav.* (2012)





Physics ABOUT BROWSE PRESS COLLECTIONS

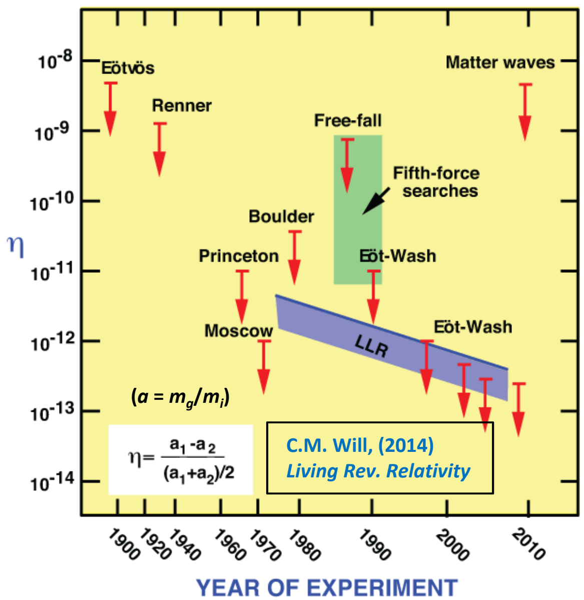
Synopsis: Space Tests of the Equivalence Principle

December 4, 2017

The MICROSCOPE satellite mission has tested the equivalence principle with unprecedented precision, showing no deviations from the predictions of general relativity.

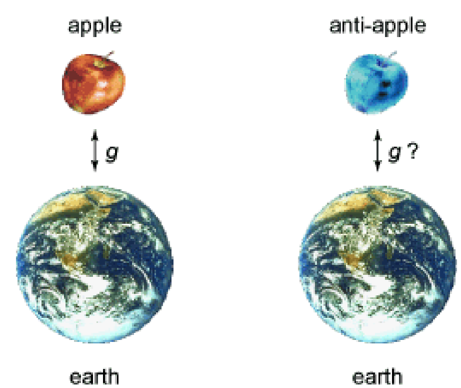
Print

MICROSCOPE Mission: First Results of a Space Test of the Equivalence Principle
Pierre Touboul *et al.*
Phys. Rev. Lett. 119, 231101 (2017)



J.G. Williams, S.G. Turyshev and D.H. Boggs, *Class. Quantum Grav. 29, 184004* (2012)

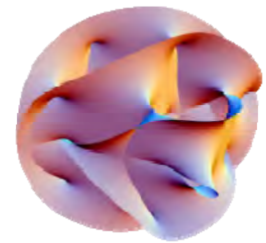
Different locations,
different masses…
…but never tested
with antimatter!



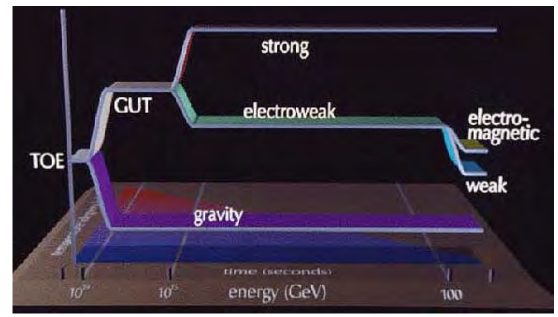
Unifying the forces of Nature

Standard Model Extension (SME):
effective field theory adding General Relativity (GR)
& CPT/Lorentz violation (LV)

***L*$_{SME}$ = *L*$_{SM}$ + *L*$_{LV}$ + *L*$_{GR}$**



Quantum gravity?



$$L = \frac{1}{2}\underbrace{(m + \frac{5}{3}N^w m^w \bar{c}^w_{TT})}_{m_{\mathrm{i,eff}}}v^2 - gz\underbrace{(m + N^w m^w \bar{c}^w_{TT} + 2\alpha N^w (\bar{a}_{\mathrm{eff}})^w_T)}_{m_{\mathrm{g,eff}}}$$

Isotropic 'Parachute' Model (IPM)

$$\frac{1}{3}m^w \bar{c}^w_{TT} = \alpha(\bar{a}_{\mathrm{eff}})^w_T$$

A. Kostelecky and J.D. Tasson, Phys. Rev. D (2011)

Matter

$$m_{\mathrm{i,eff}} = m_{\mathrm{g,eff}}$$
$$\mathrm{a} = g$$

Antimatter

$$m_{\mathrm{i,eff}} \neq m_{\mathrm{g,eff}}$$
$$\bar{\mathrm{a}} = g(1 - \frac{4m^w N^w}{3m}\bar{c}^w_{TT})$$

different acceleration
(not "antigravity")

$$\mathbf{V} = \underbrace{-\mathbf{G}\,\frac{\mathbf{mm'}}{\mathbf{r}}}_{\text{Newton}}\underbrace{(1 \mp \mathbf{a}\ \mathbf{e}^{-\frac{r}{v}} + \mathbf{b}\ \mathbf{e}^{-\frac{r}{s}})}_{\text{Supergravity : one component of repulsive gravity}}$$

Antigravity – a crazy idea? (J. Scherk, Phys. Lett. B, 1979)
Gravitational acceleration of Antimatter (Nieto and Goldman, Phys. Rep., 1991)
Negative mass – antigravity in General Relativity (G. Chardin, Hyp. Int. 1997)

The goal of GBAR – test EP with antimatter

GBAR (CERN AD-7): Free fall of antihydrogen (at rest!)

Witteborn & Fairbank, Nature (1968):
gravitational fall of the positron (E_g = 6E-11 V/m !)

M. Holtzscheiter et al. (CERN PS-200):
gravitational fall of the antiproton

Gabrielse et al. (CERN AD-2) Phys. Rev. Lett. (1999):
trapped antiproton/proton comparisons (indirect)

CPLEAR Collaboration, Phys. Lett. B (1999):
kaon-antikaon limits (indirect)

Supernova 1987A, e.g. Phys. Rev. D (1989):
(anti)neutrino time of flight (hypothesis)

Cassidy et al. Phys. Rev. Lett. (2015):
Rydberg Ps for free fall experiment

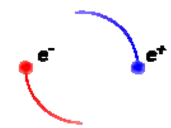
The AEgIS Collaboration (CERN AD-6):
Interferometry of neutral antihydrogen beam

The ALPHA-g Collaboration (CERN AD-5):
Neutral antihydrogen

use of anti-hydrogen ions (for sympathetic cooling)

J. Walz and T.W. Haensch, *Gen. Rel. Grav*. 36, 561 (2004)

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



P. Pérez & A. Rosowsky, *NIM* A 545, 20 (2005)

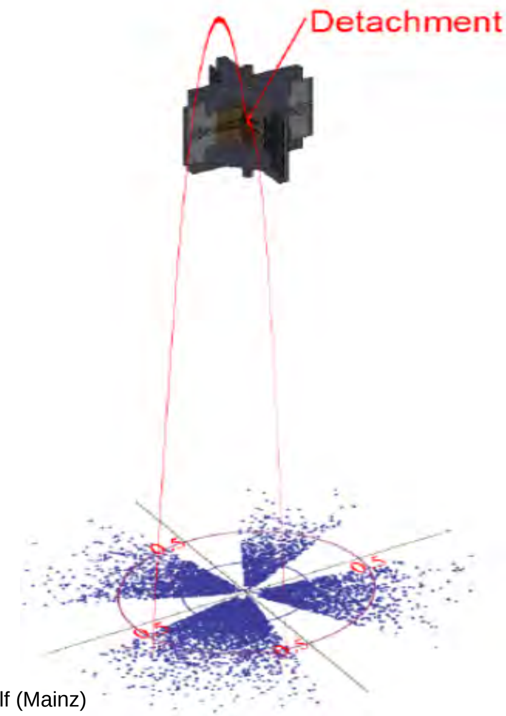
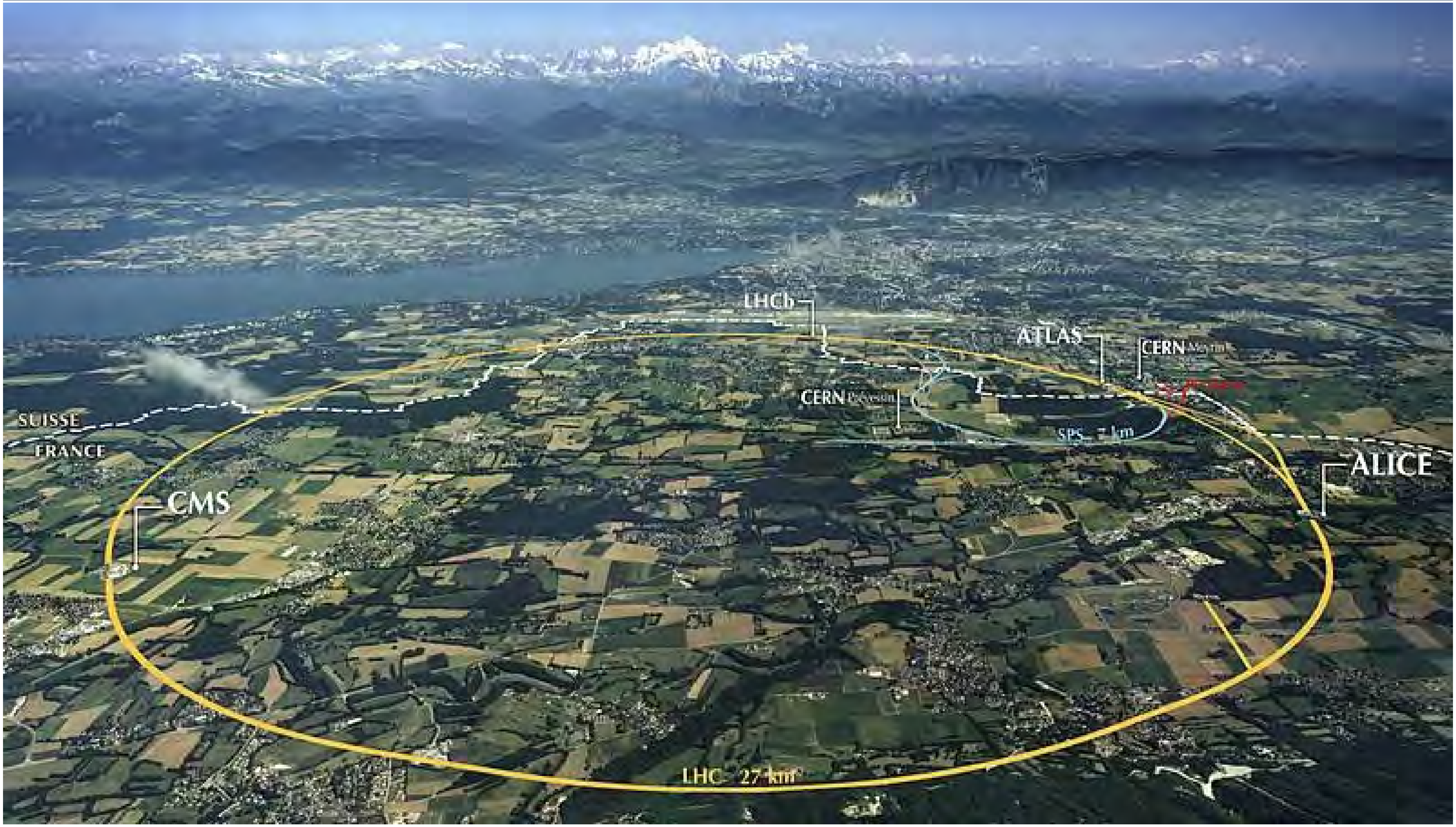
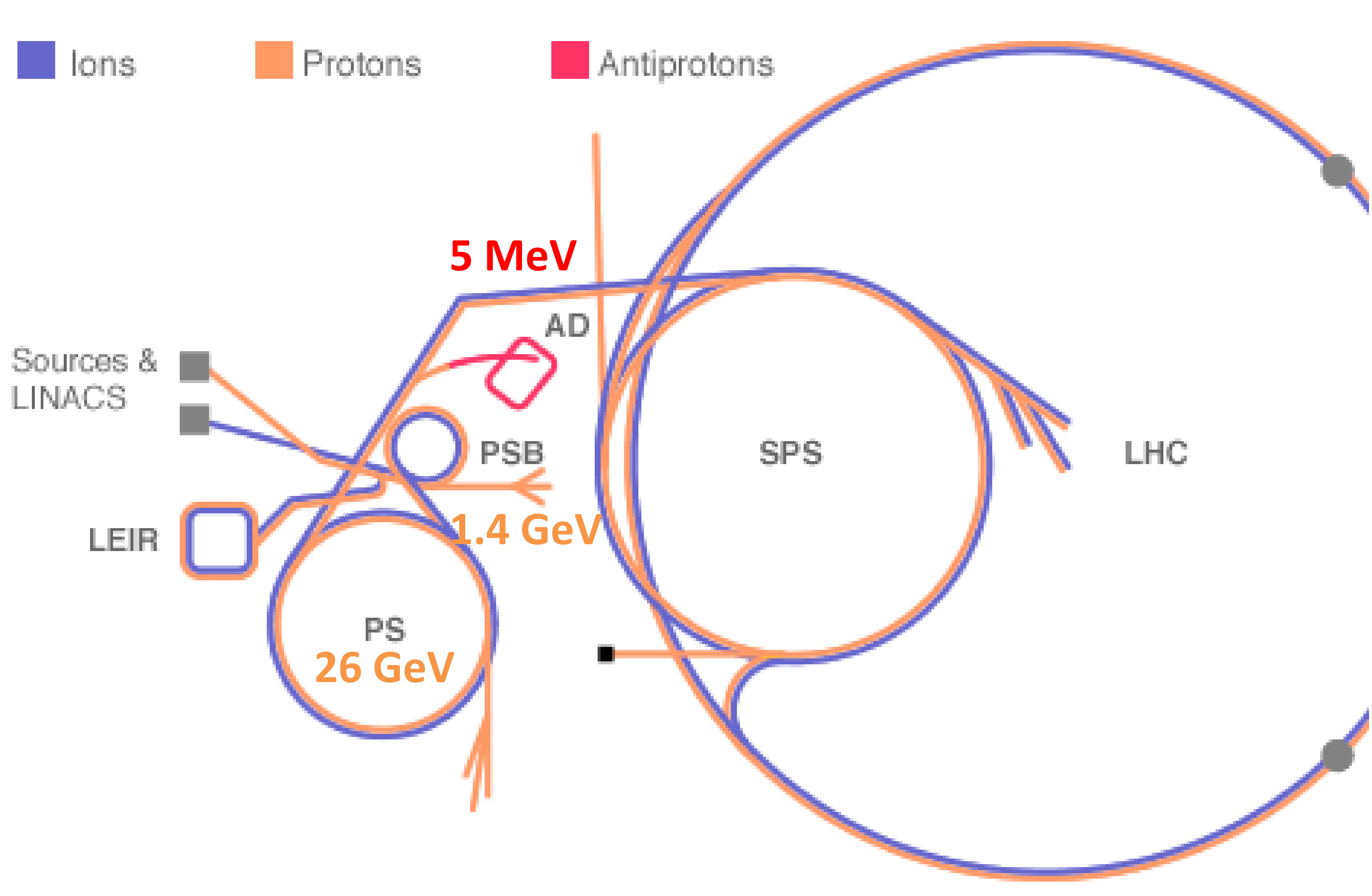


Image: S. Wolf (Mainz)

CERN – home of antimatter

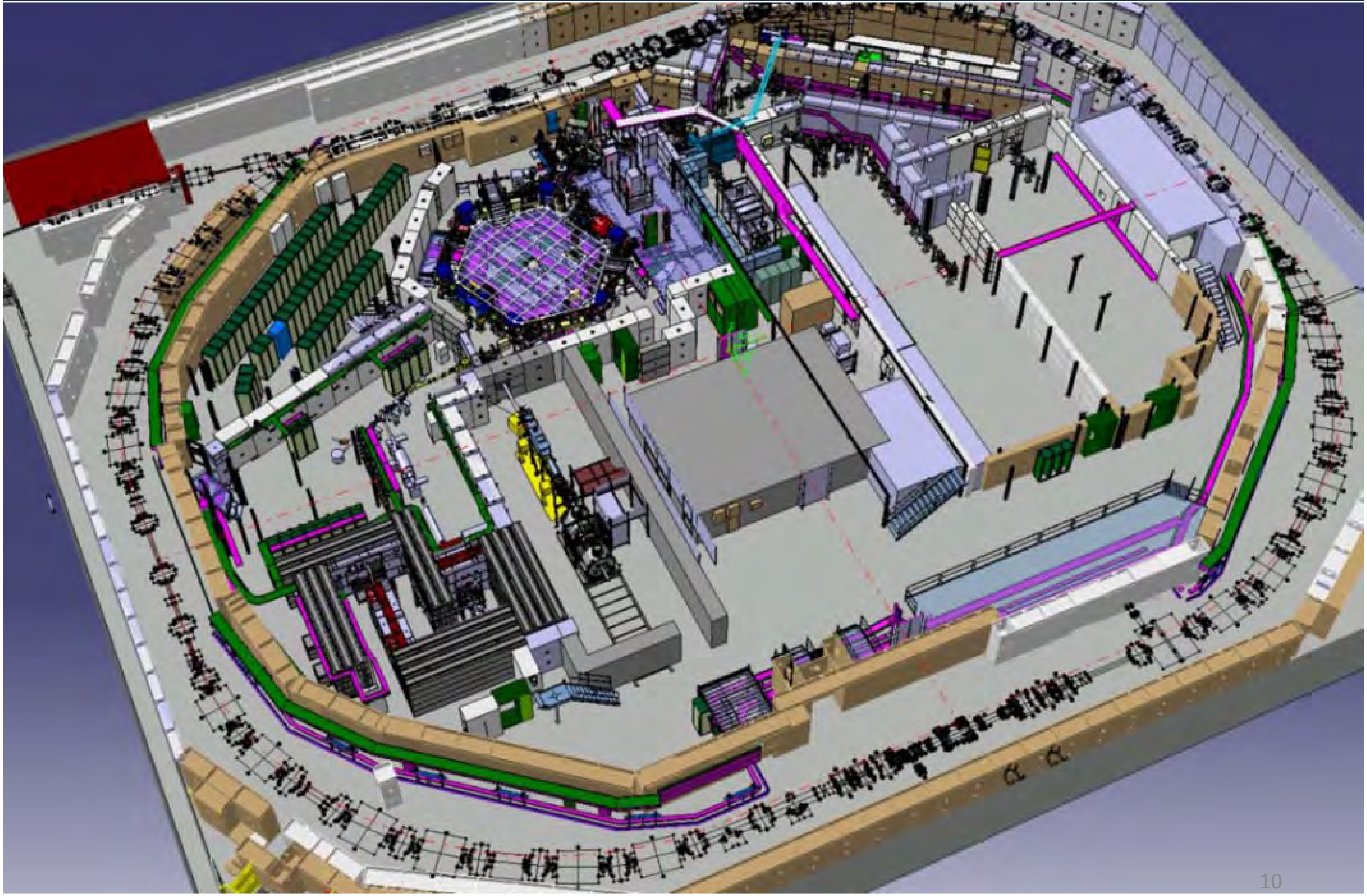


The CERN accelerator chain



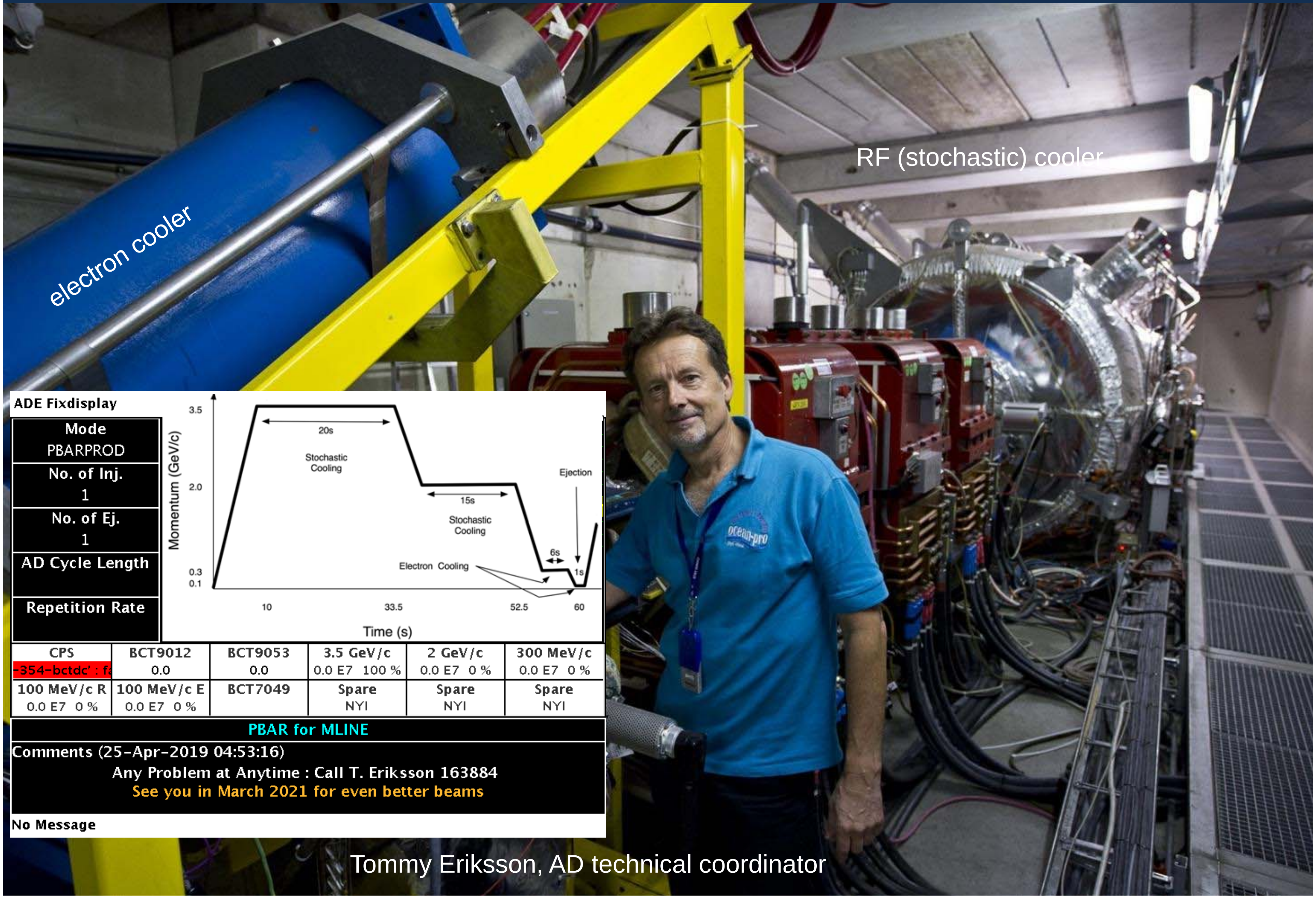
The AD – CERN's "antimatter factory"

The AD (Antiproton Decelerator) facility



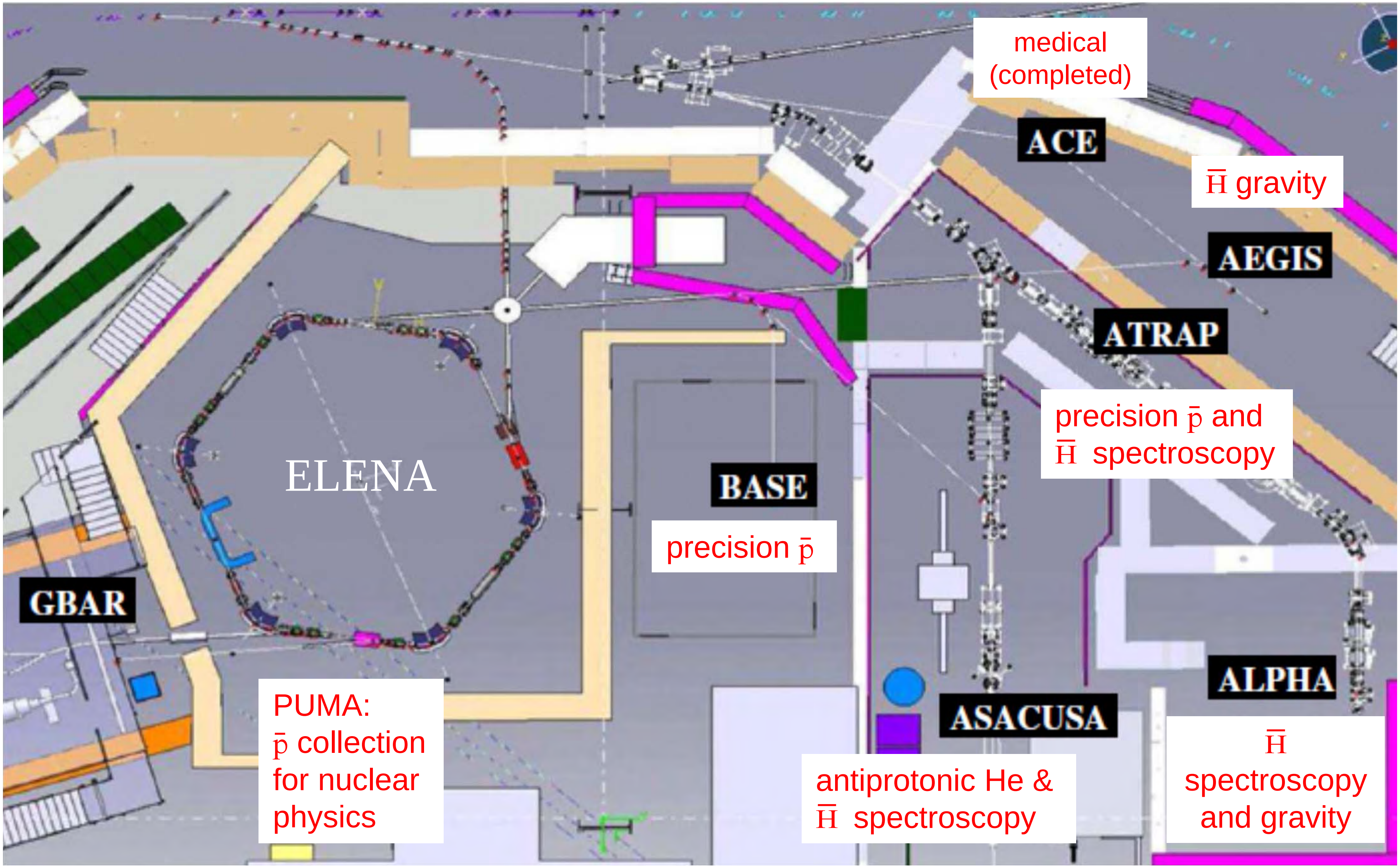
The AD storage ring

The AD coolers (needed for deceleration)

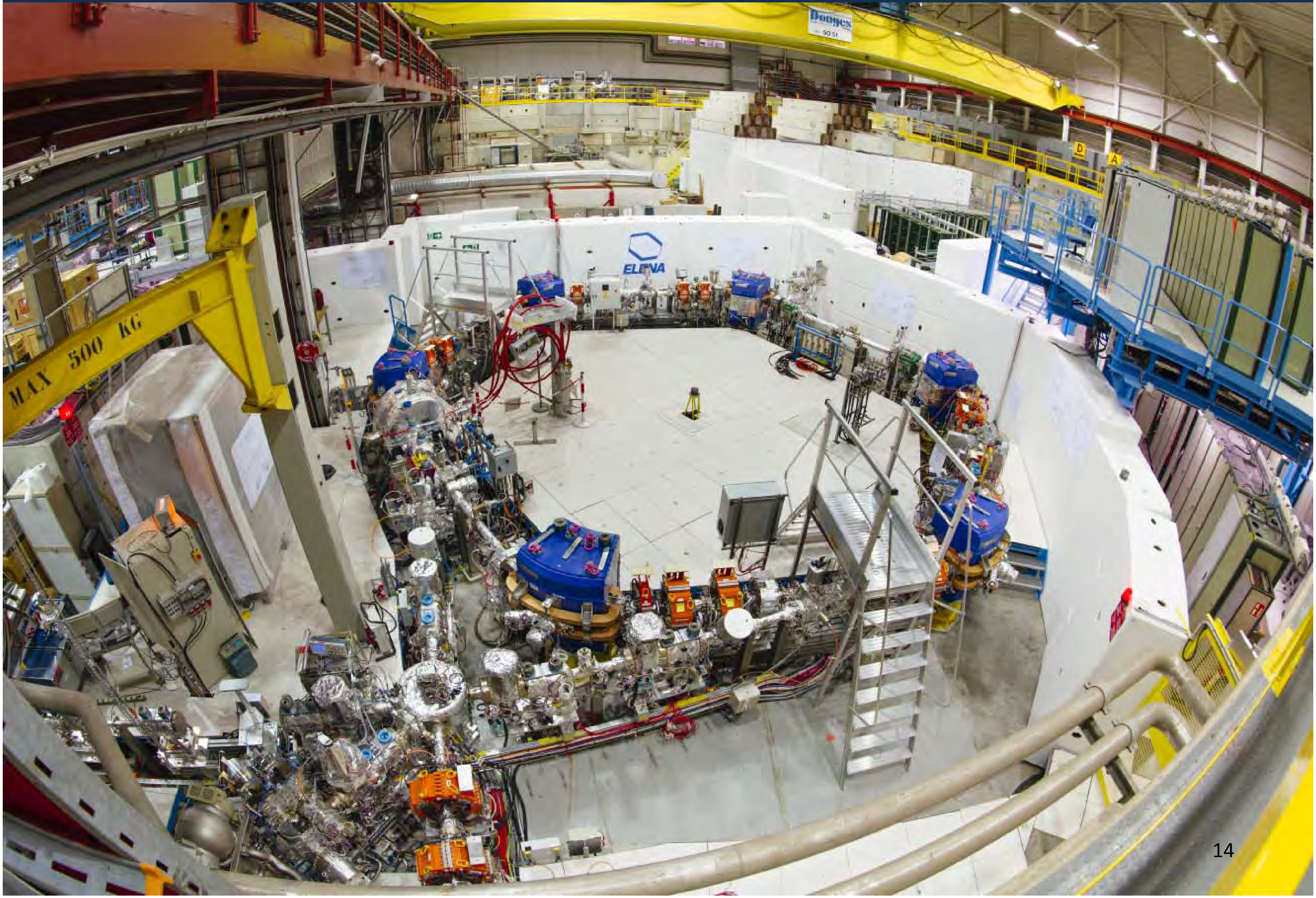


Tommy Eriksson, AD technical coordinator

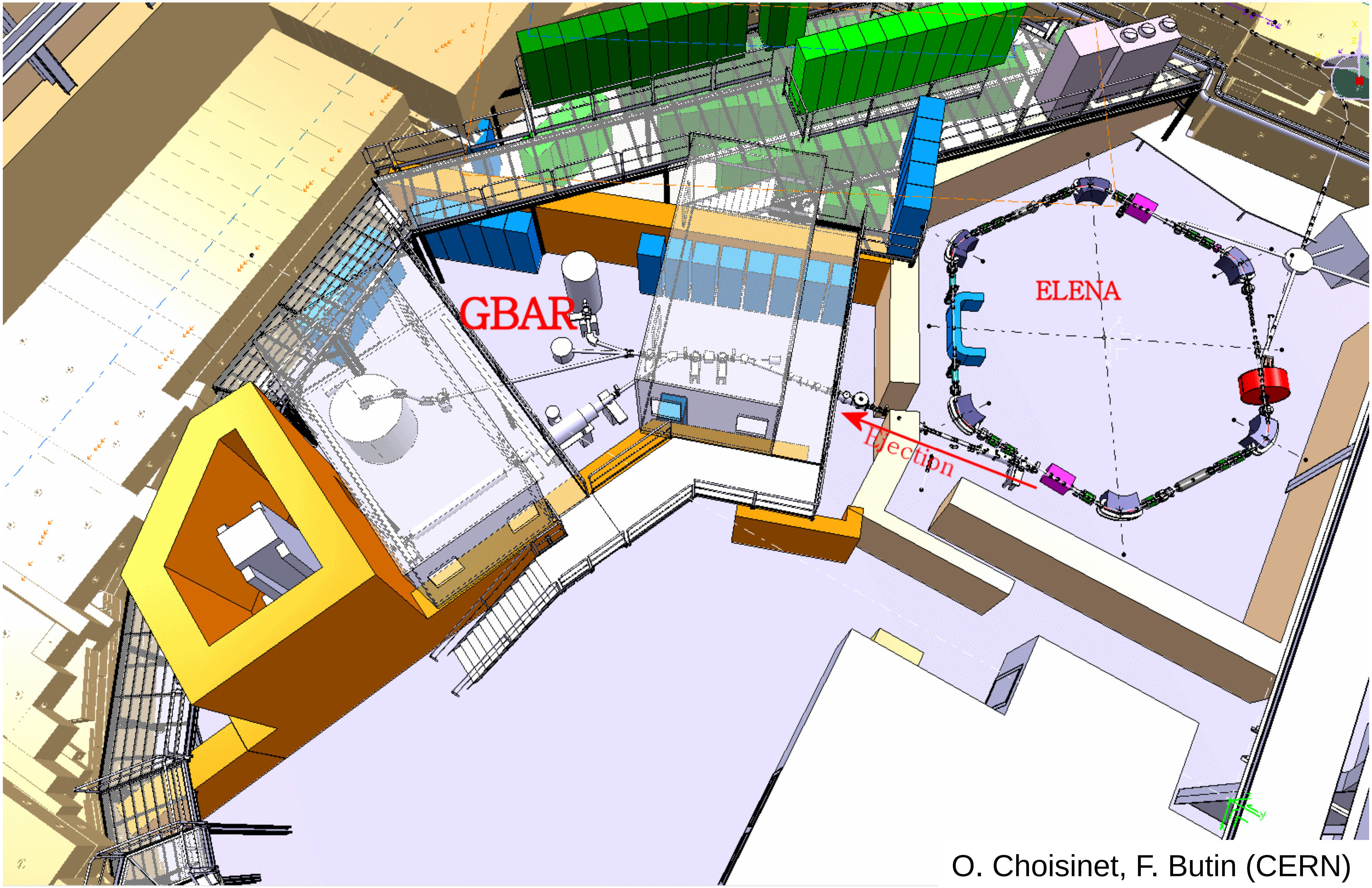
AD Experimental Hall



Extra Low ENergy Antiproton ring

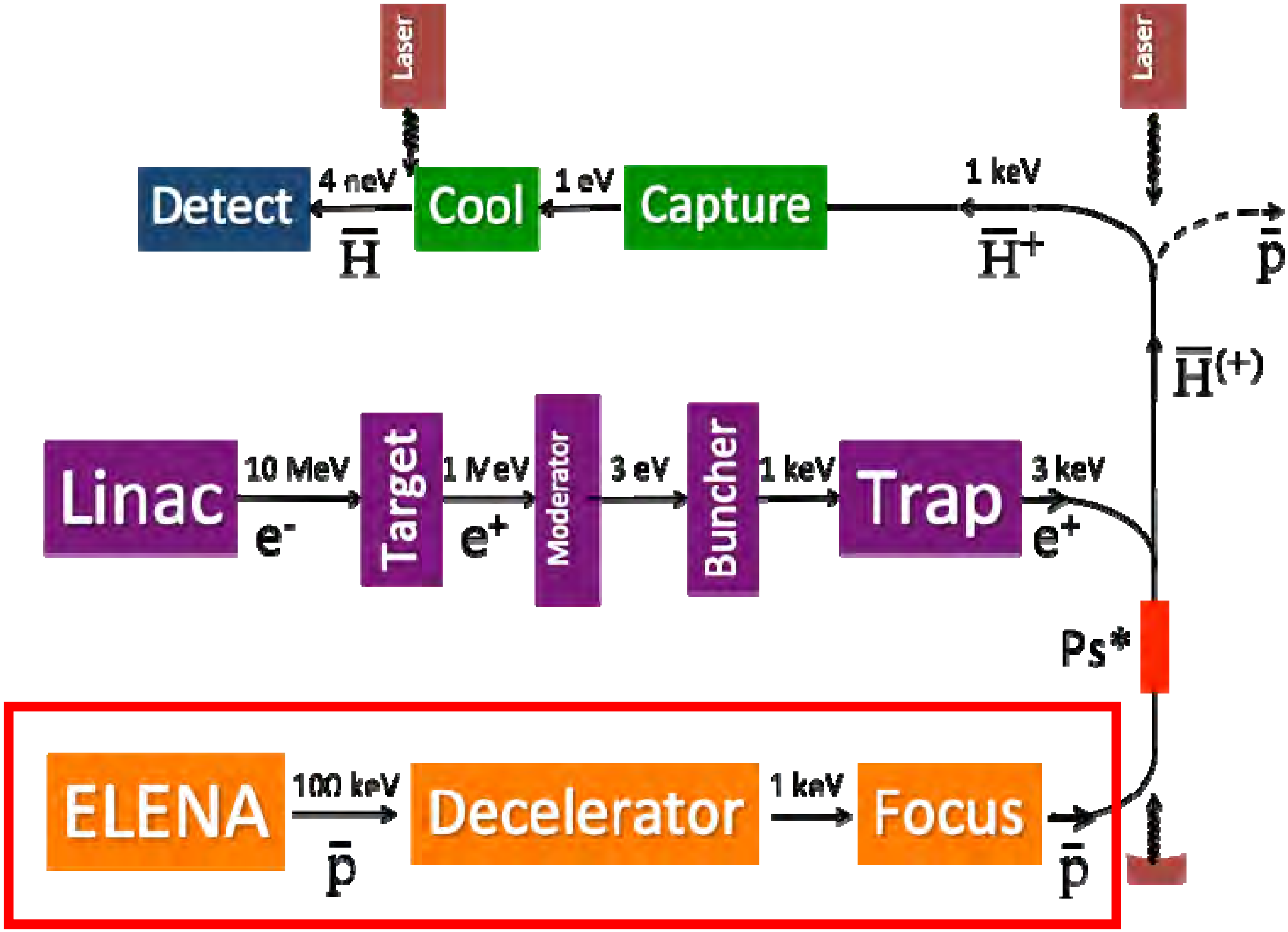


present GBAR layout

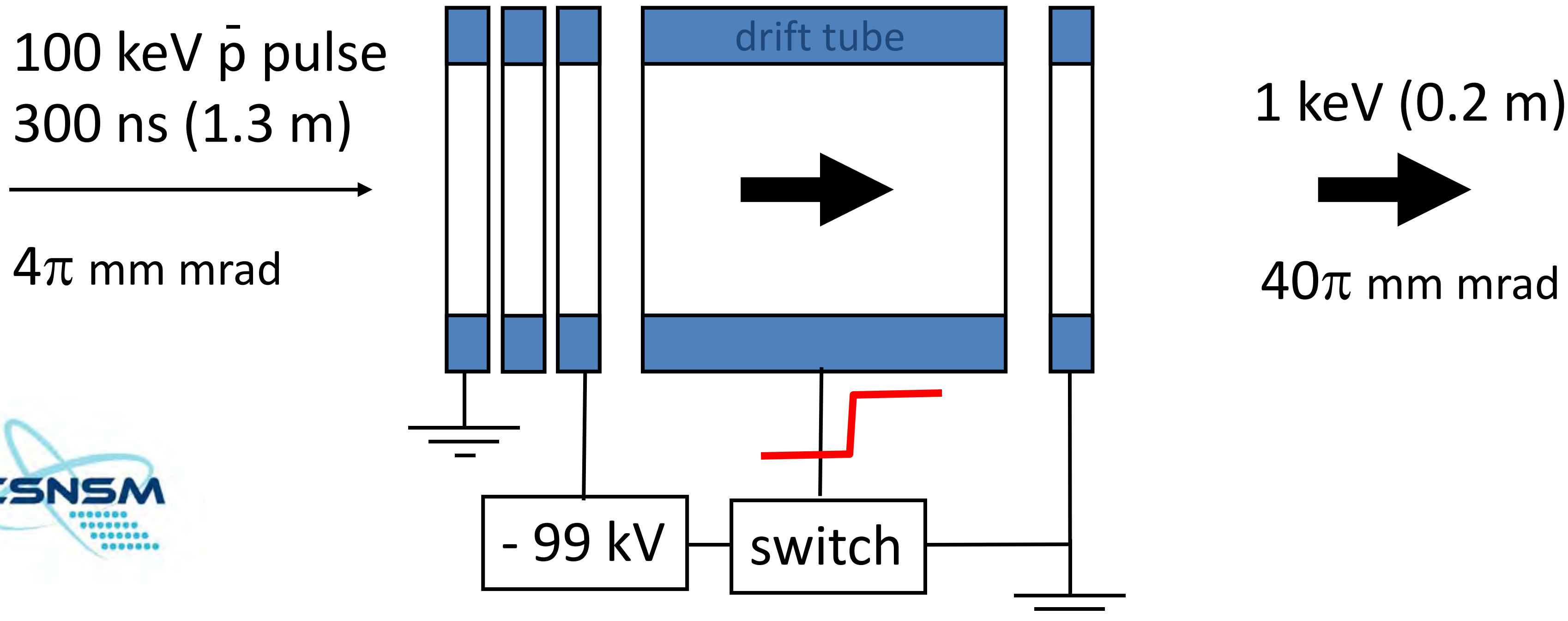


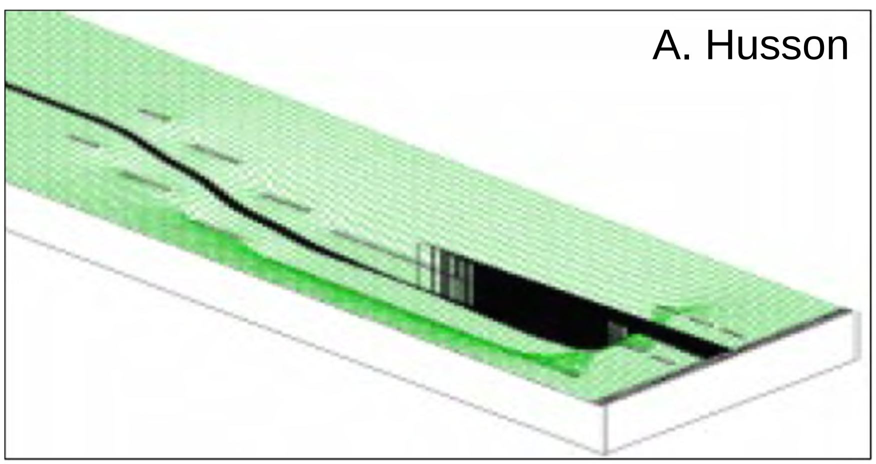
O. Choisinet, F. Butin (CERN)

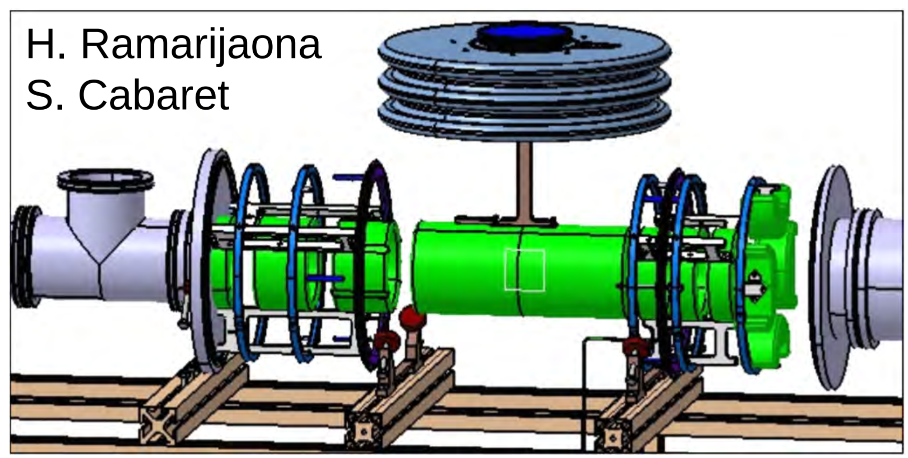
GBAR Schematic



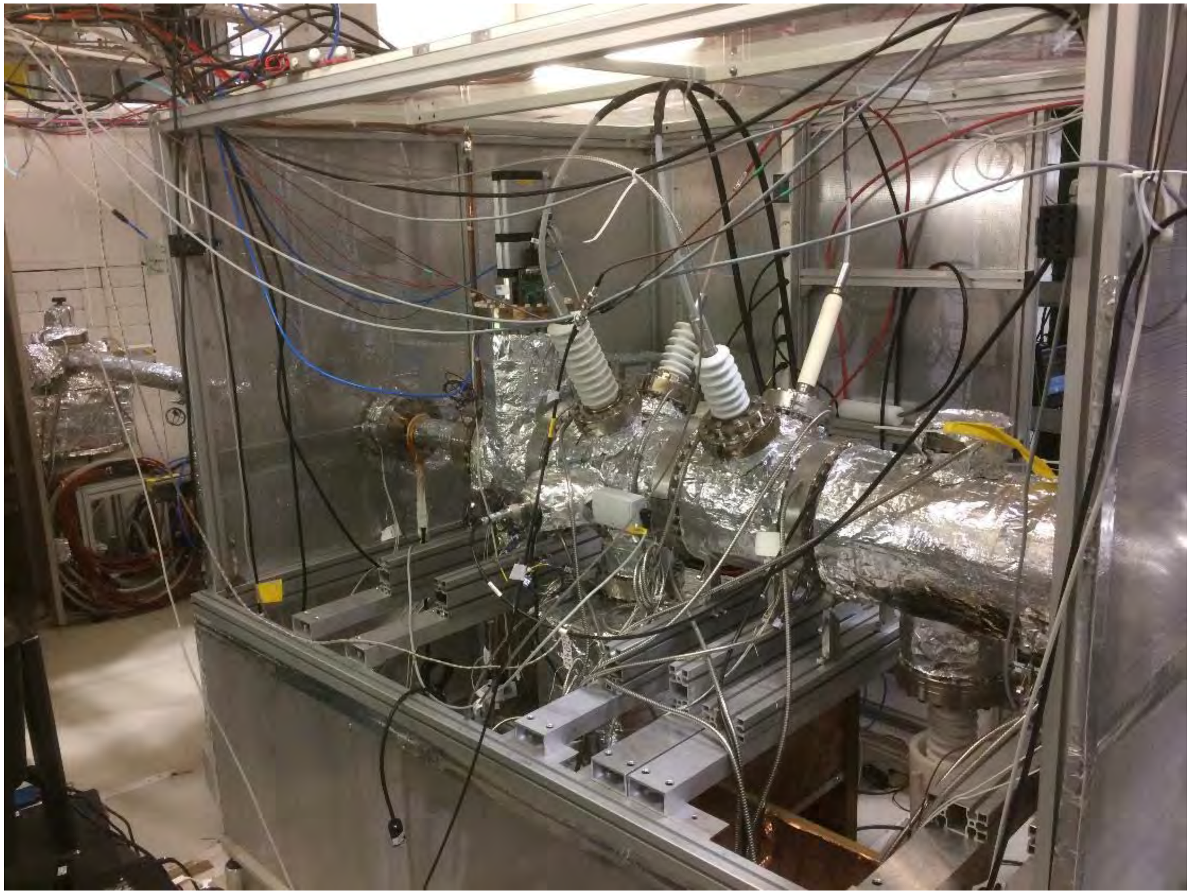
GBAR antiproton decelerator schema



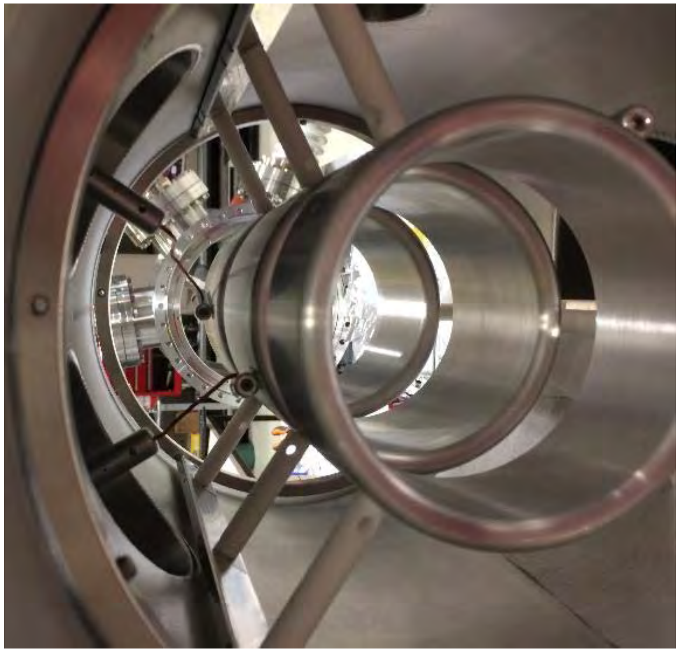




GBAR antiproton decelerator setup



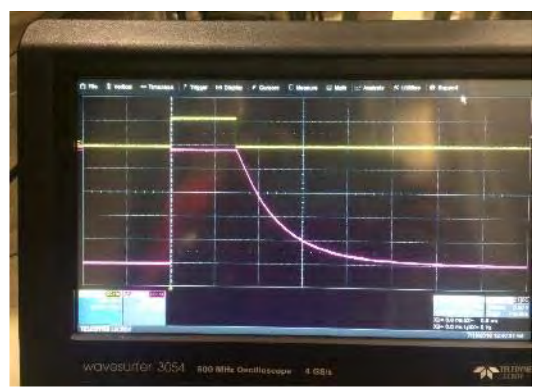
decelerator connected to ELENA



electrodes

A. Husson (CSNSM) PhD thesis (2018)
B. Kim (SNU) and A. Welker (CERN)

GBAR decelerator HV switch



drift tube 0.4 m

100 keV $\bar{p}$ → 230 ns/m

10 keV $\bar{p}$ → 720 ns/m

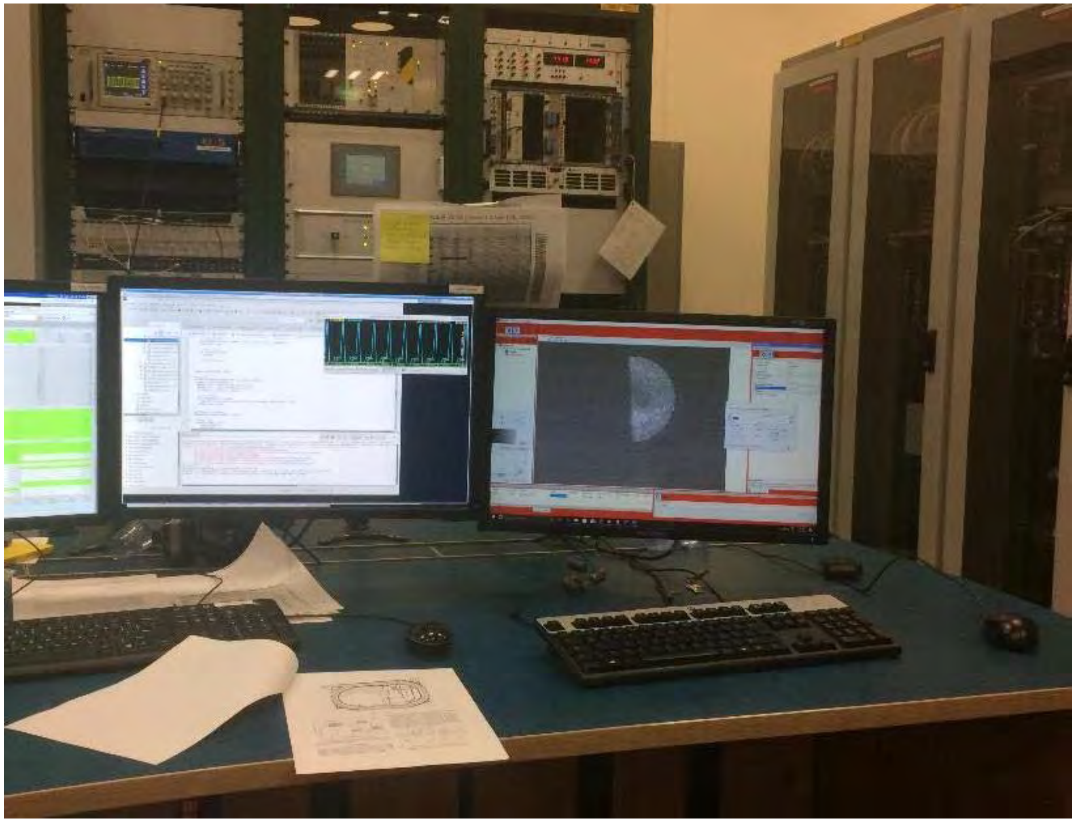
risetime 280 ns

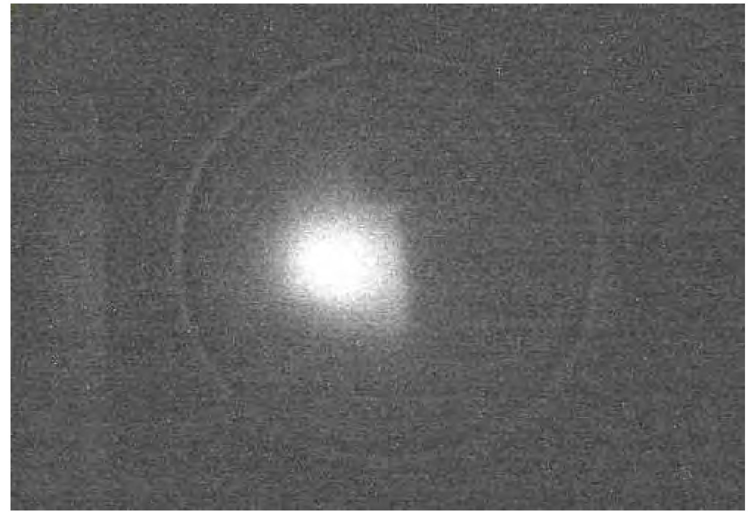
A. Husson (CSNSM) PhD thesis (2018)

First beams from ELENA

H^- : July 10, 2018

$\bar{p}$: July 20, 2018

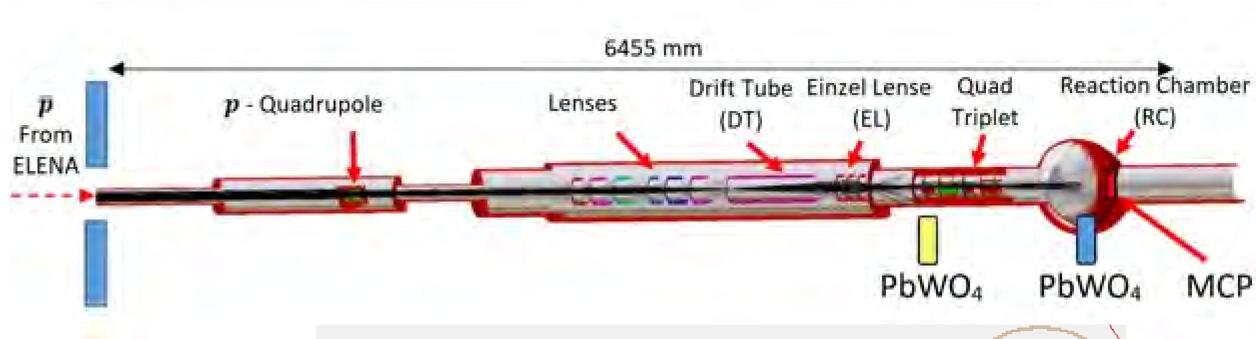


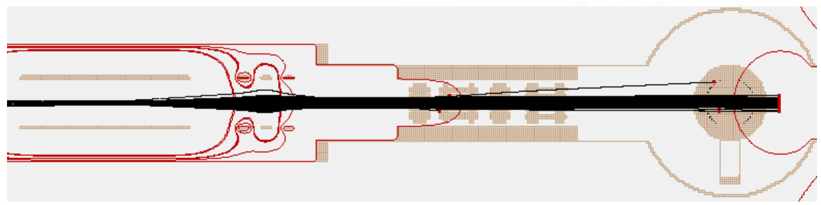


beams from ELENA:
$\bar{p}$ every 110 s
H^- 5 s

A. Welker, B. Kim, L. Liszkay, B. Mansoulié & the ELENA team

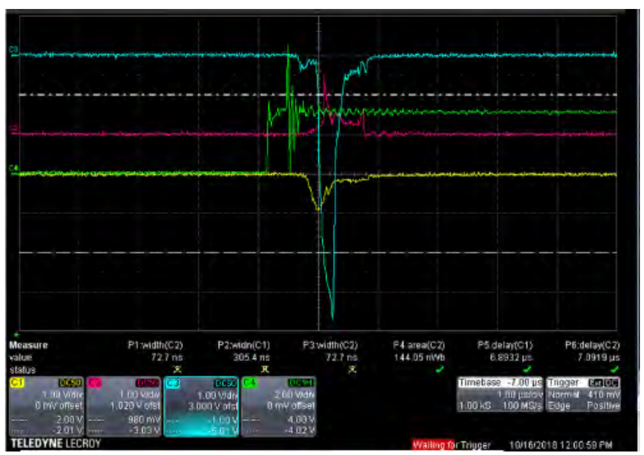
$\bar{p}$ beam on MCP in reaction chamber

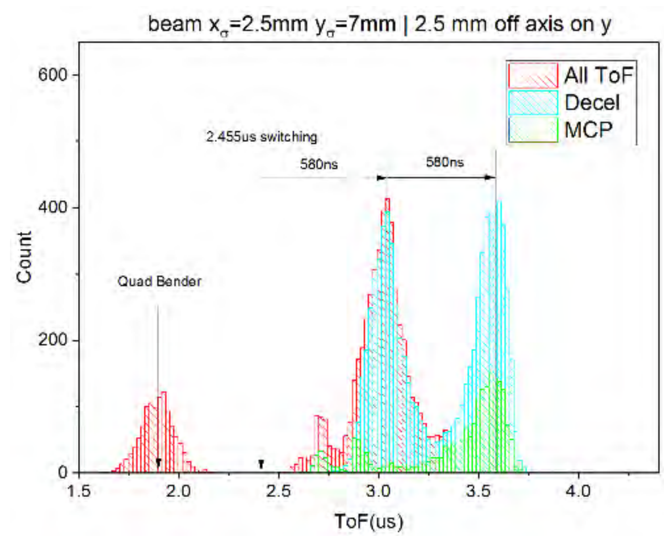




Simulation
(A. Welker)

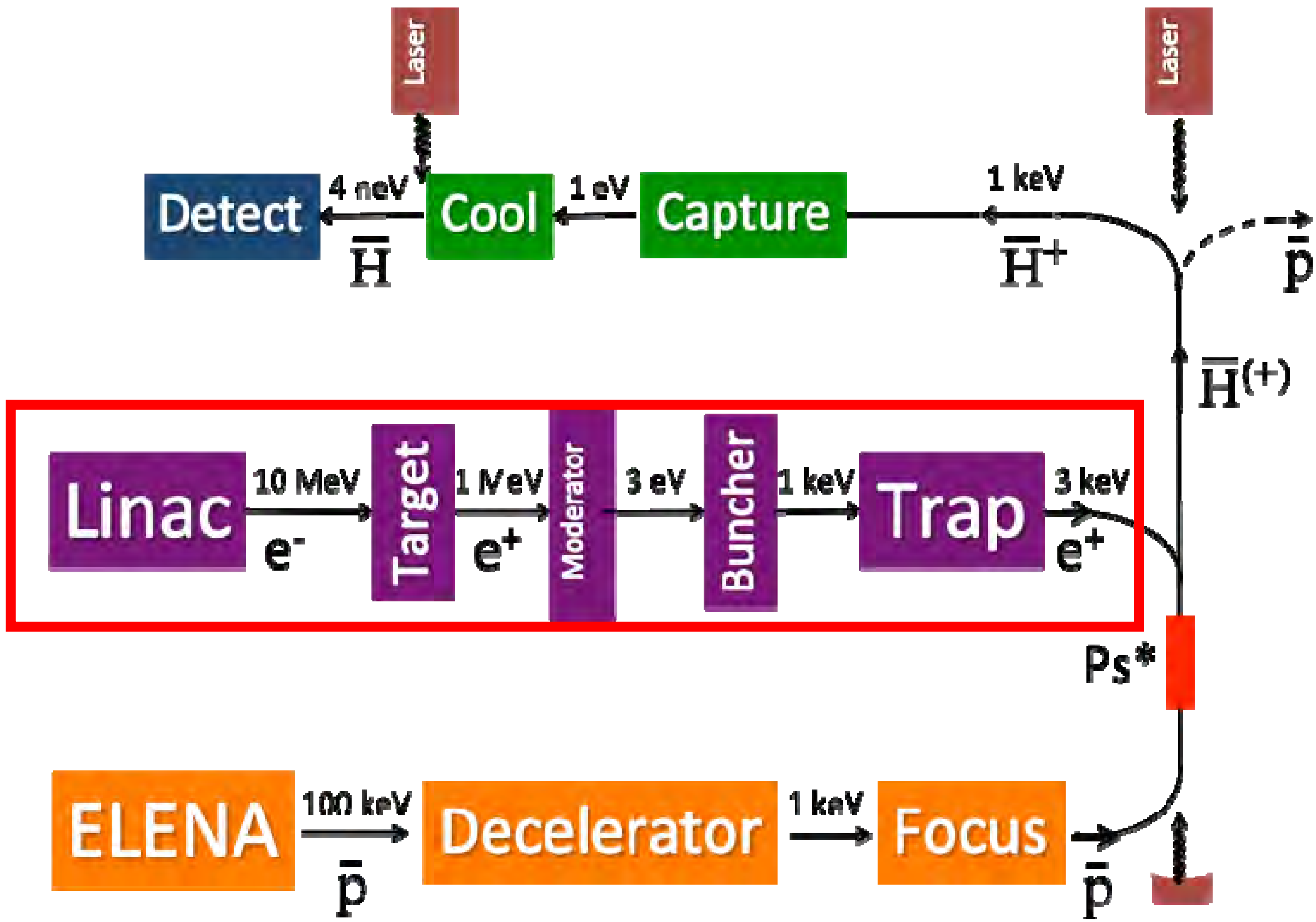
Real event



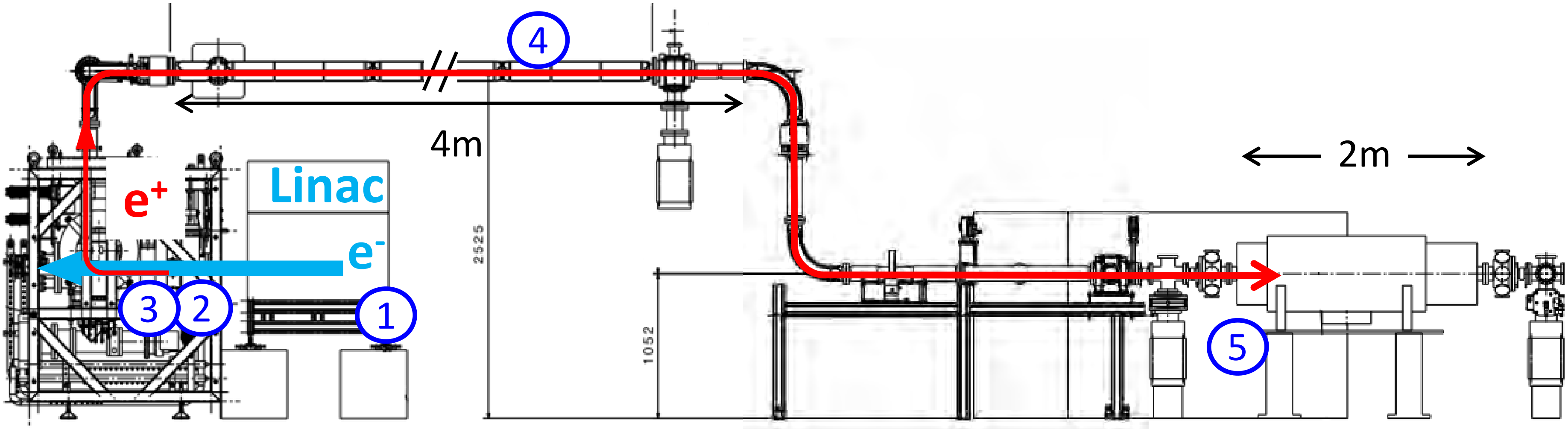


Beam Size = FWHM (5 mm)
Transversal Energy Spread = 1 keV
Beam on axis ~ 25% is decelerated (so ~ 10^6 $\bar{p}$)

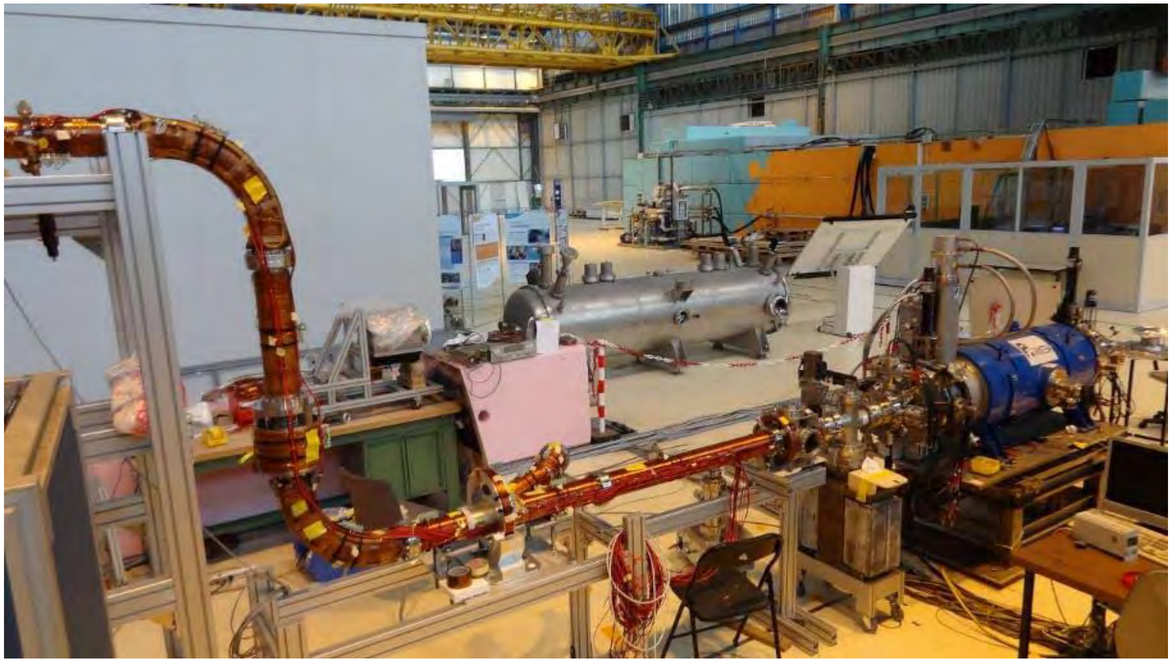
GBAR Schematic



e^+ demonstrator in Saclay

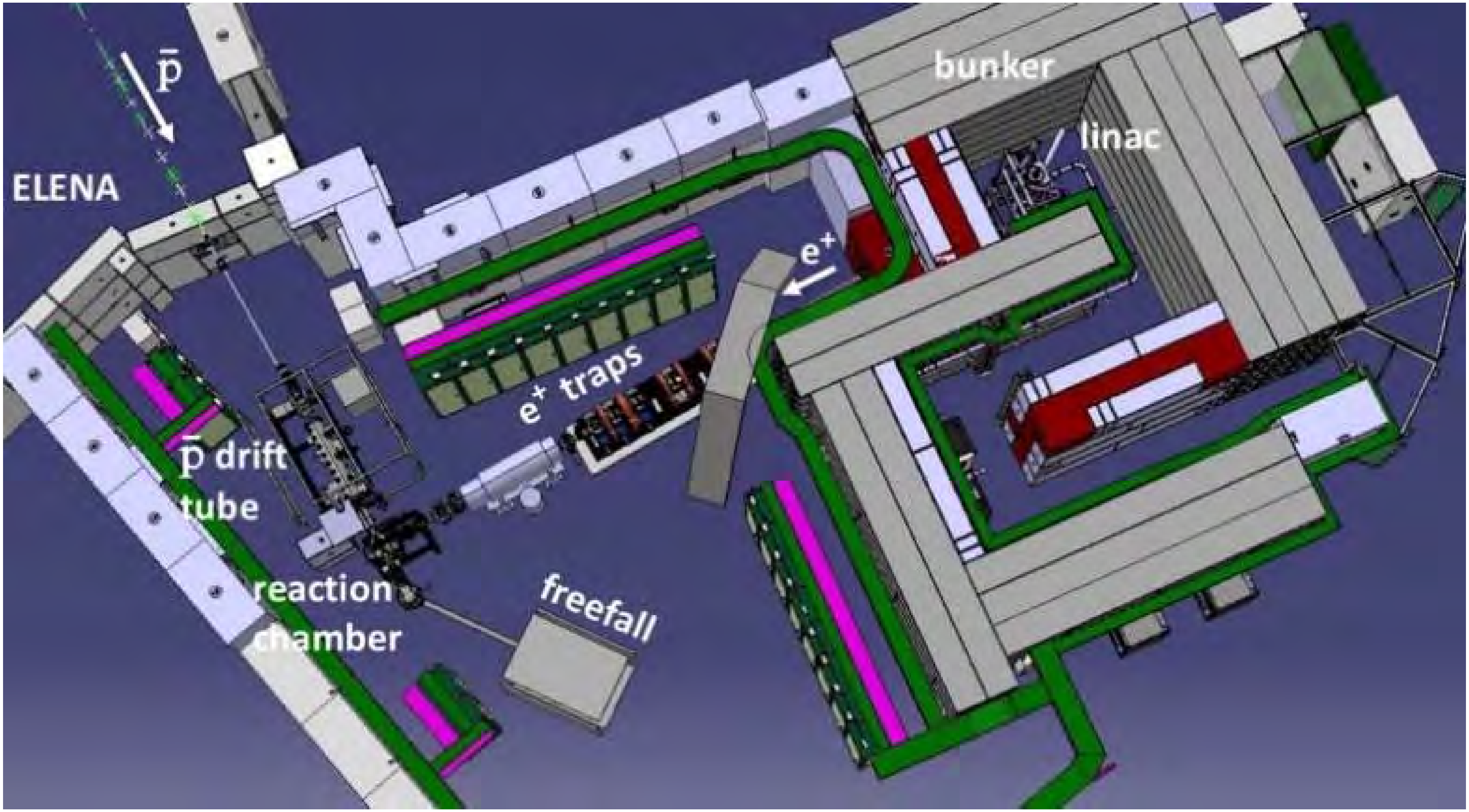


1. Linear electron accelerator (4.3 MeV)
2. Converter e^-/e^+
3. e^+ moderater
4. Magnetic (solenoidal) transfer line
5. 5-T Penning-Malmberg trap from RIKEN



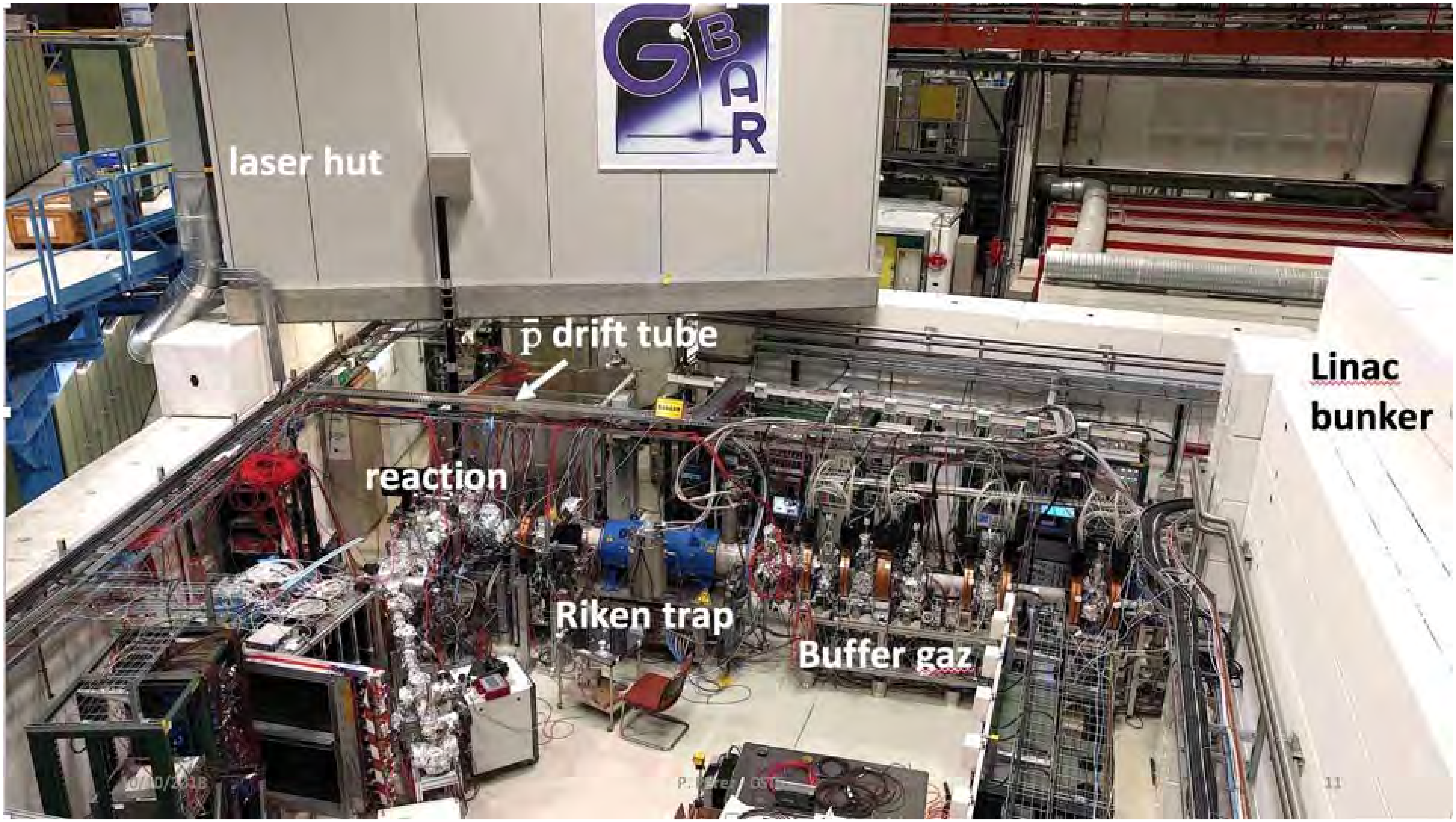
P. Grandemange (CSNSM) PhD thesis (2013)

GBAR layout at CERN-AD



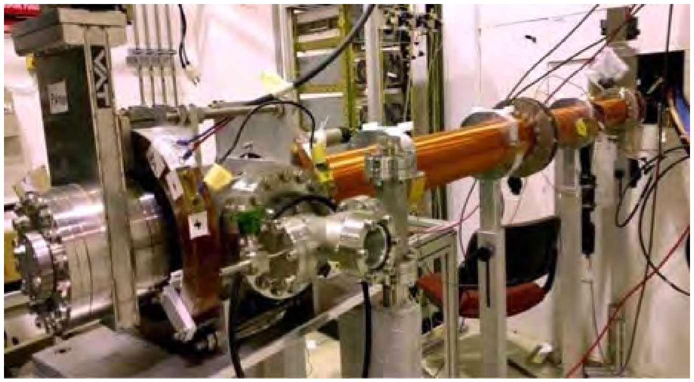
Ph. Hardy, J.-Y. Rousse

March 2017

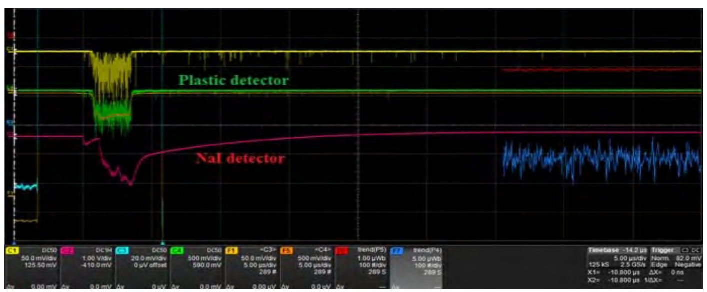

laser hut
p̄ drift tube
Linac
bunker
reaction
Riken trap
Buffer gaz

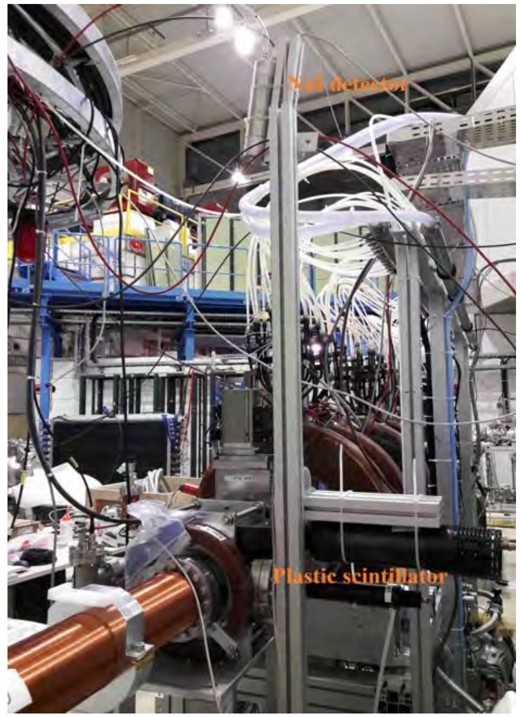
10-MeV, 300 Hz linac from NCBJ (Swierk, Poland)

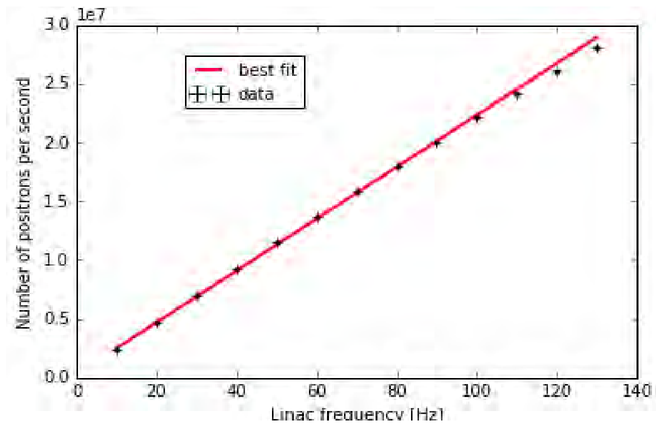
Measuring positron flux



e^+ beam line exiting the bunker

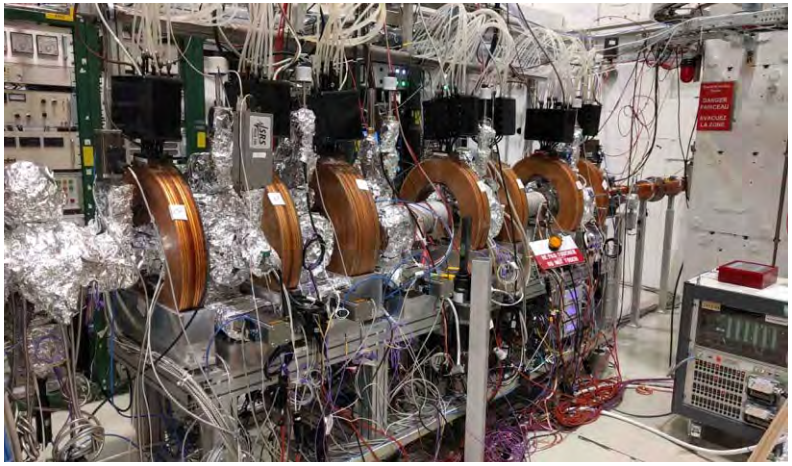


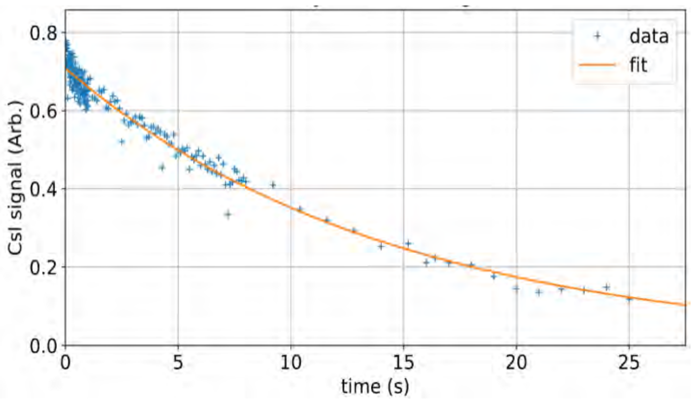




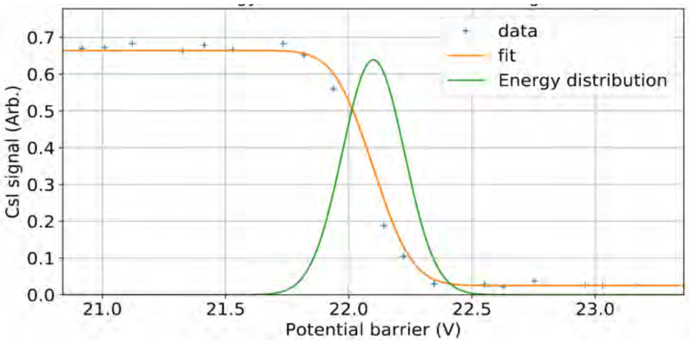
- 3×10^5 e^+ / pulse initially
- 10% loss per bunch from 10 to 130 Hz
- 2×10^7 e^+ / s (100 Hz)
- Extrapolation to 300 Hz → 6×10^7 e^+ / s
- Will improve moderation (x 2 ?)
- Goal 3×10^8 e^+ / s

Buffer Gas trap



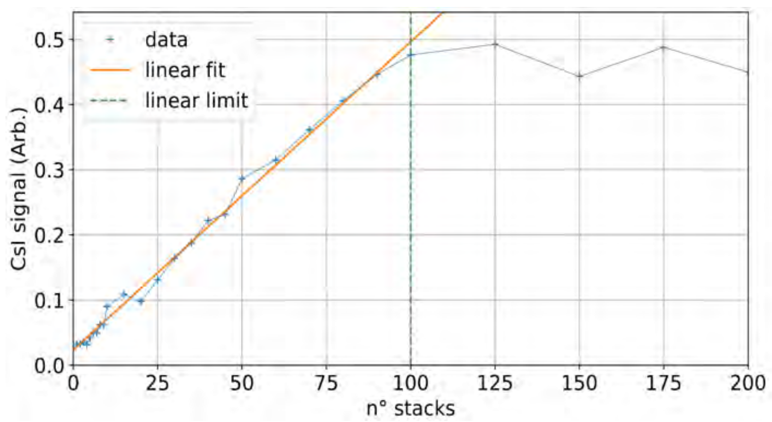


N_2 with CO_2 cooling gas
present trapping efficiency 5 ± 0.5% (goal 20-25%)
lifetime 0.6 s (stage 1) and 14s (stage 3)
ΔE = 130 meV (stdev)
80 bunches from linac stacked and transferred

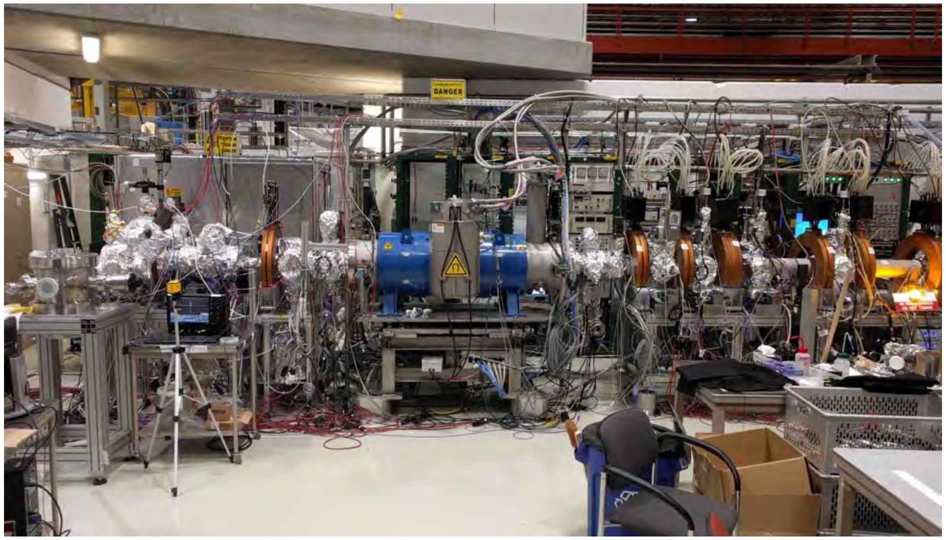


Dirk Van der Werf (U. Swansea)
A. Leite (IRFU) PhD thesis (2017)
Samuel Niang (IRFU) PhD thesis

High field positron trap



saturation >100 stacks from buffer gas trap
with present potential well shape

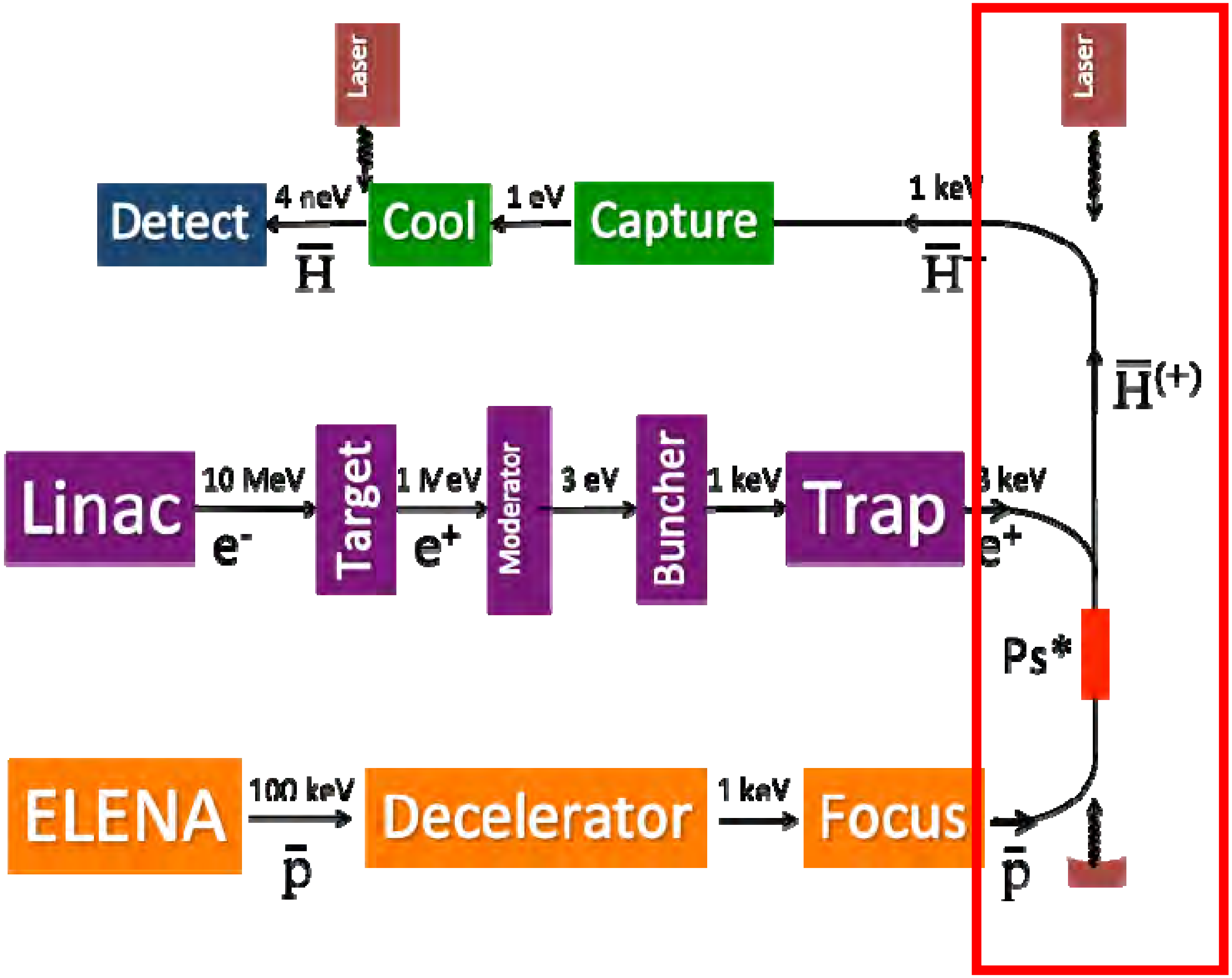


With linac at 100 Hz → 1 x 10^8 e^+ in 100 s
Goal: accumulate 3 x 10^{10} e^+ in 110 s

e^+ lifetime in trap > 20 min
plasma diameter 80 μm using rotating wall (3 MHz / 1 V)

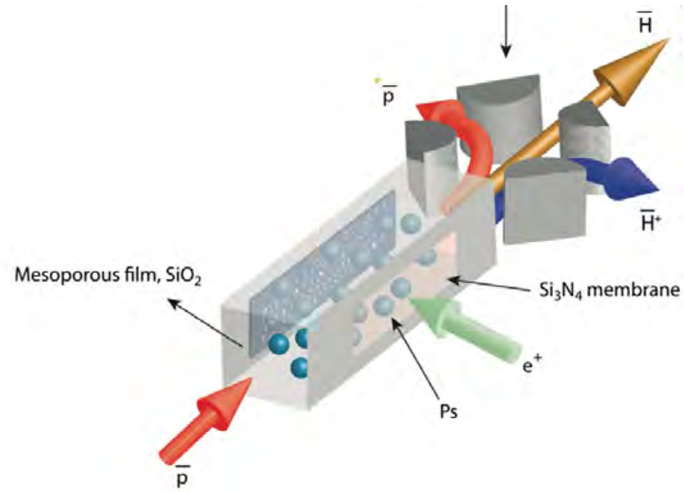
Pierre Grandemange (CSNSM) PhD thesis (2013)
Samuel Niang (IRFU) PhD thesis

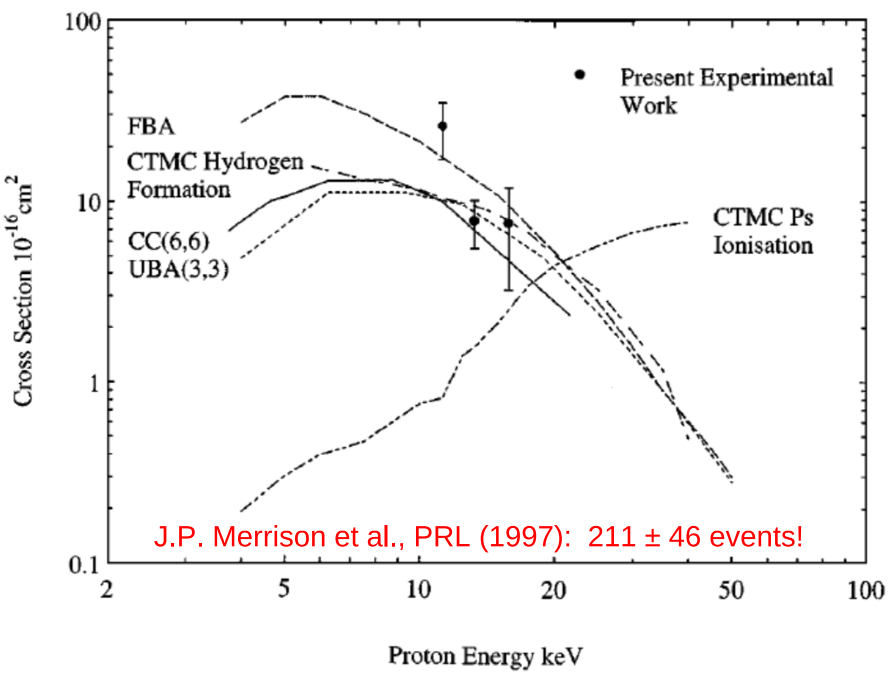
GBAR Schematic

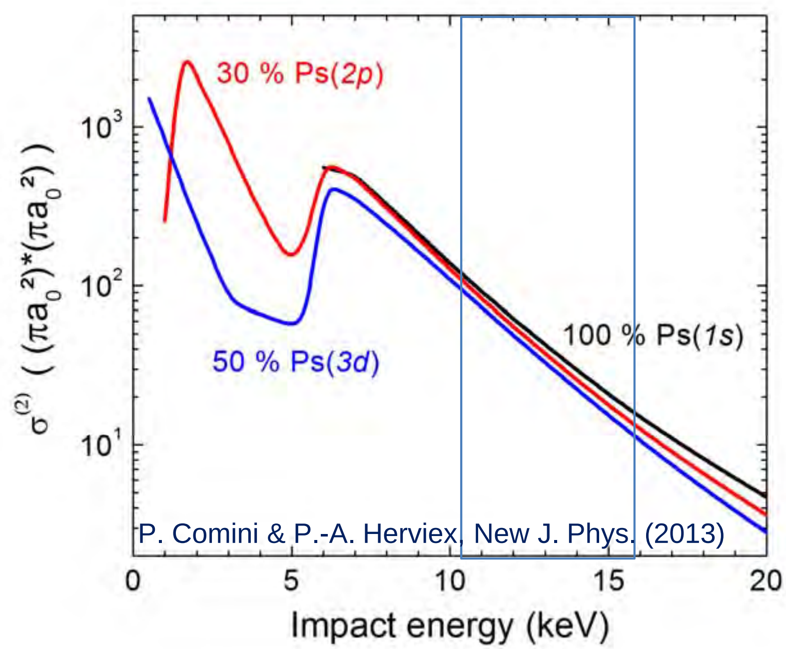


Antihydrogen ion production

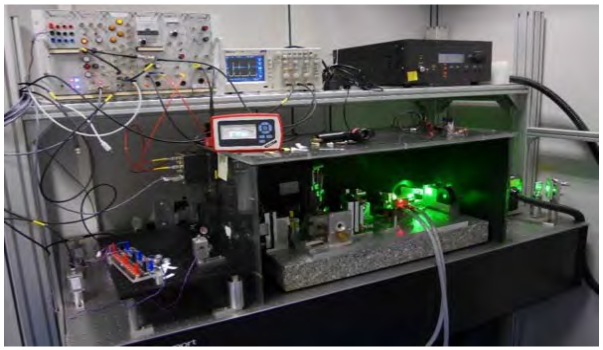
$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$
$$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$$



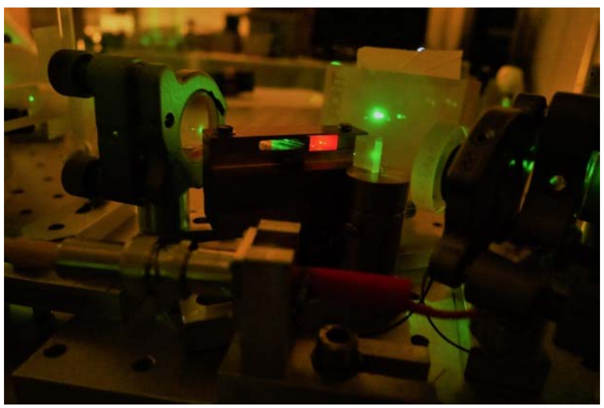




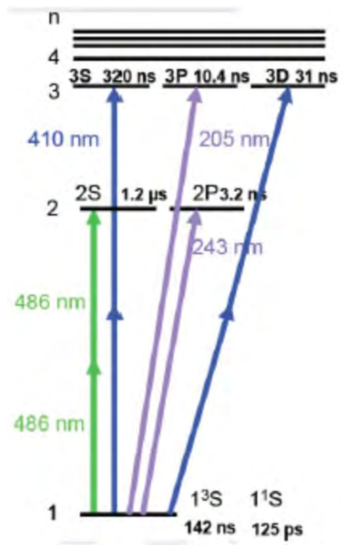
Ps excitation laser

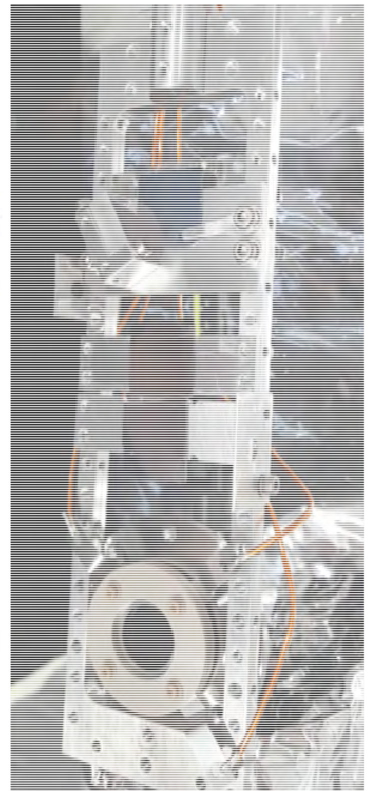


CW TiSa seeder, 260 mW at 820 nm

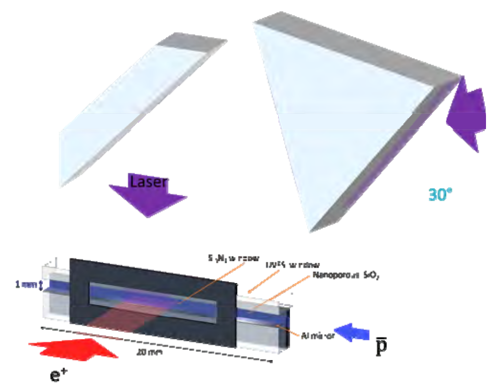


TiSa oscillator, >5 mJ at 820 nm
9 mJ obtained at 410 nm (with TiSa ampli)





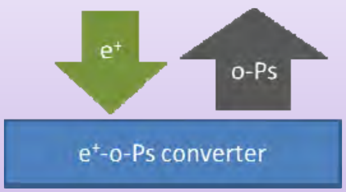
sample holder, MCP, mirror

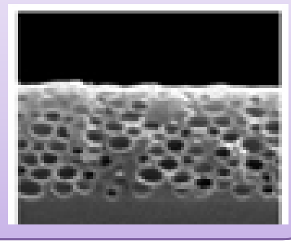


beam paths to Ps target

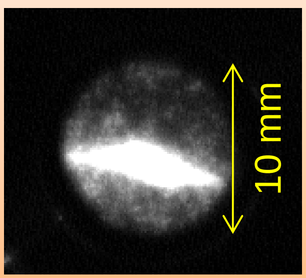
First ortho-positronium signal for GBAR@CERN

Positron-positronium converter (mesoporous SiO_2)

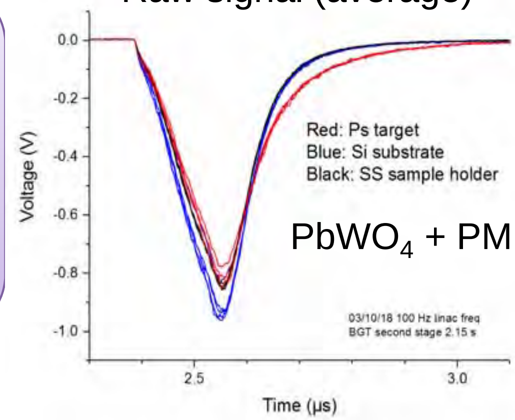


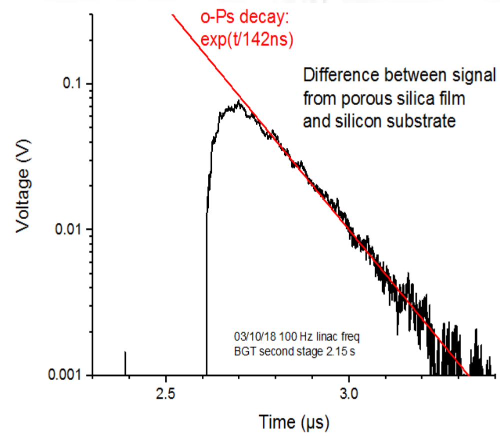


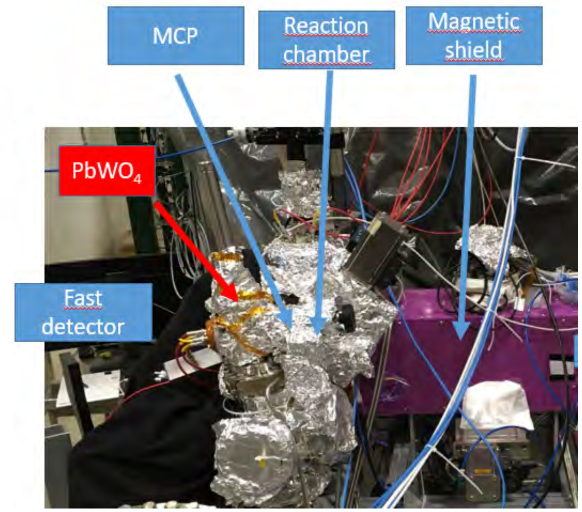
Positron beam spot on the target



Raw signal (average)



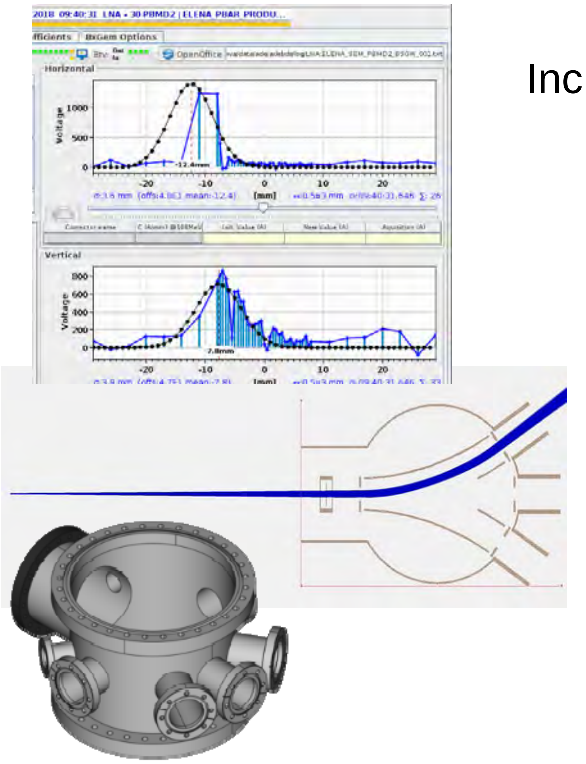


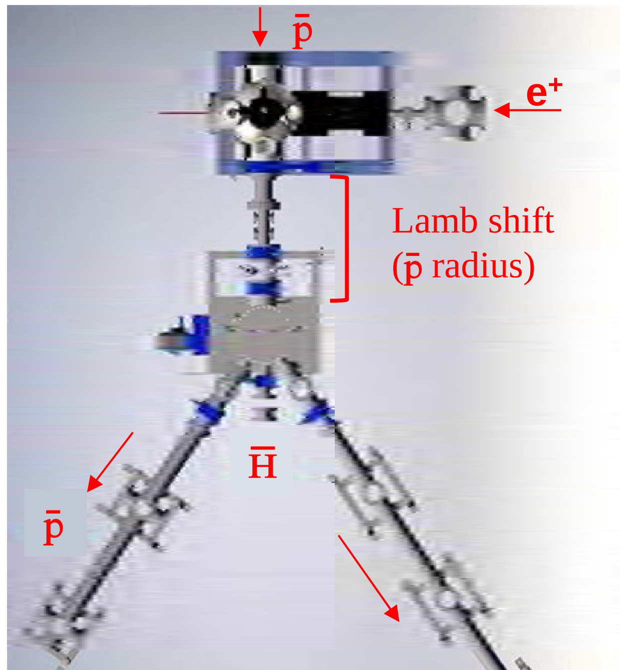


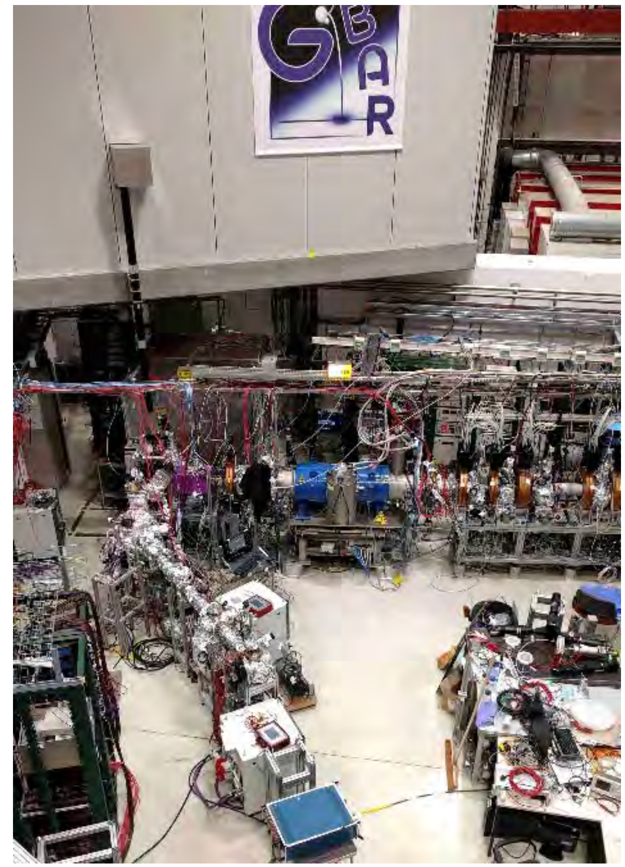
Differential signal showing oPs lifetime

11 November 2018: GBAR attempts Antihydrogen!

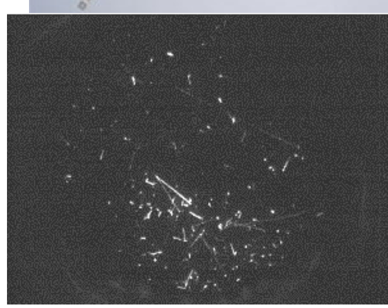
Included ELENA commissioning and debugging diagnostics…





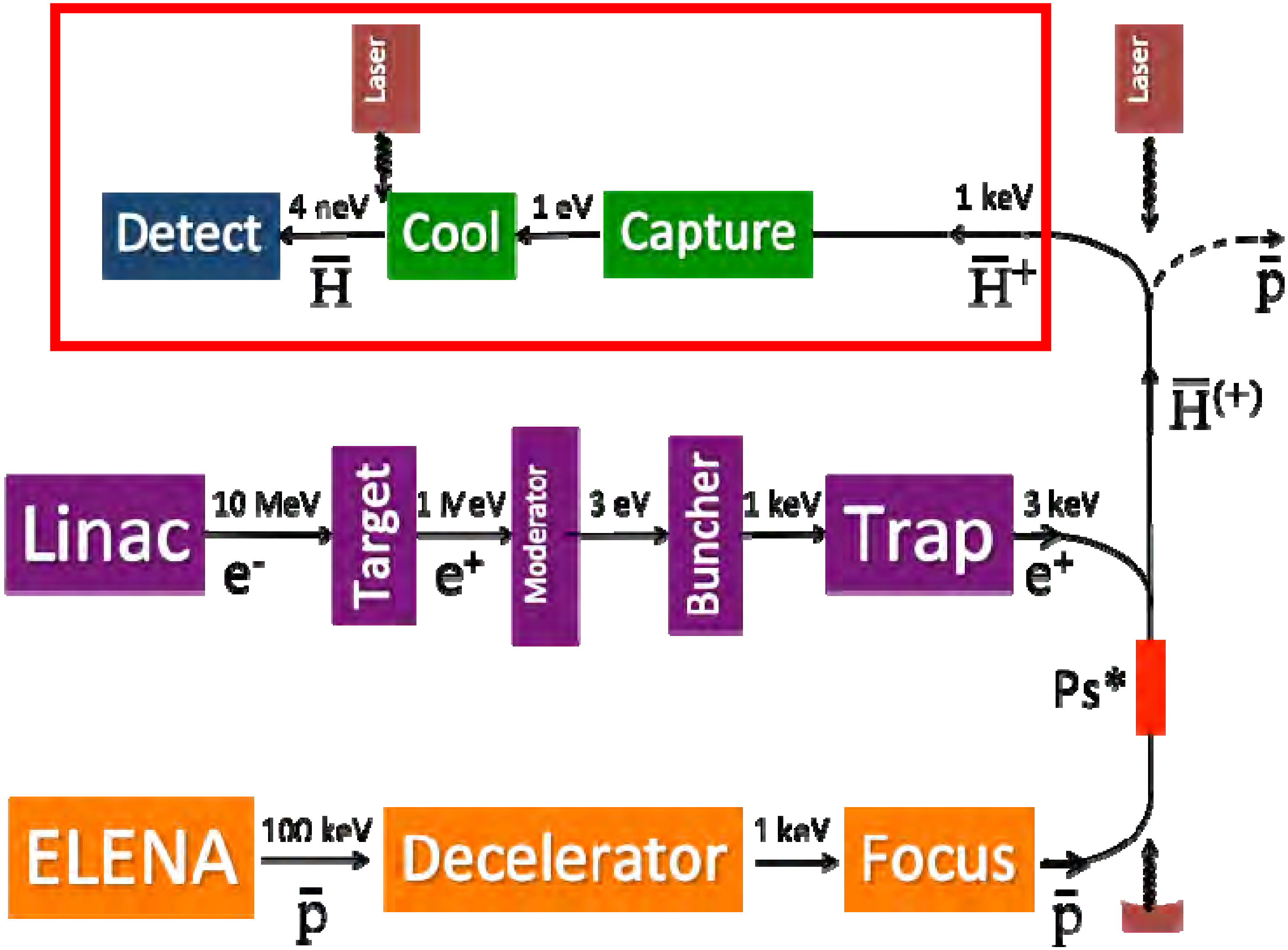


B. Latacz (IRFU) PhD. thesis

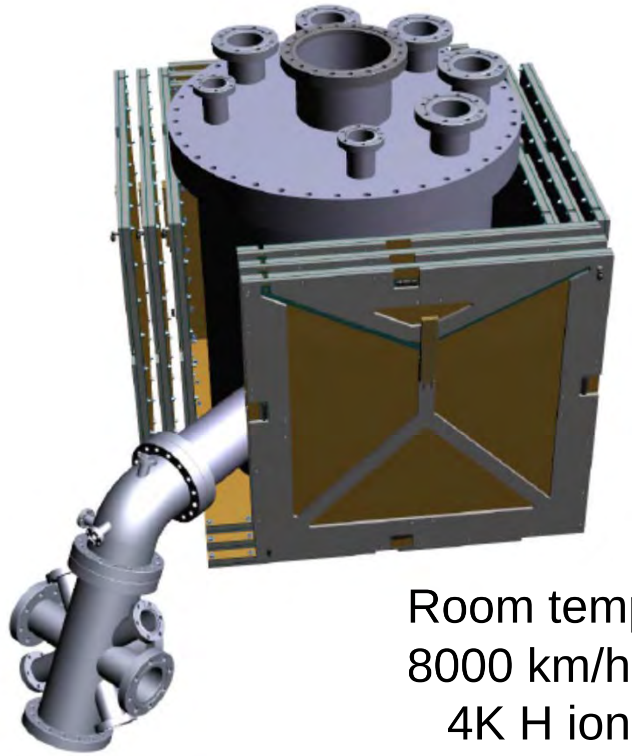


antiprotons in MCP
(no $\bar{H}$ ☹)

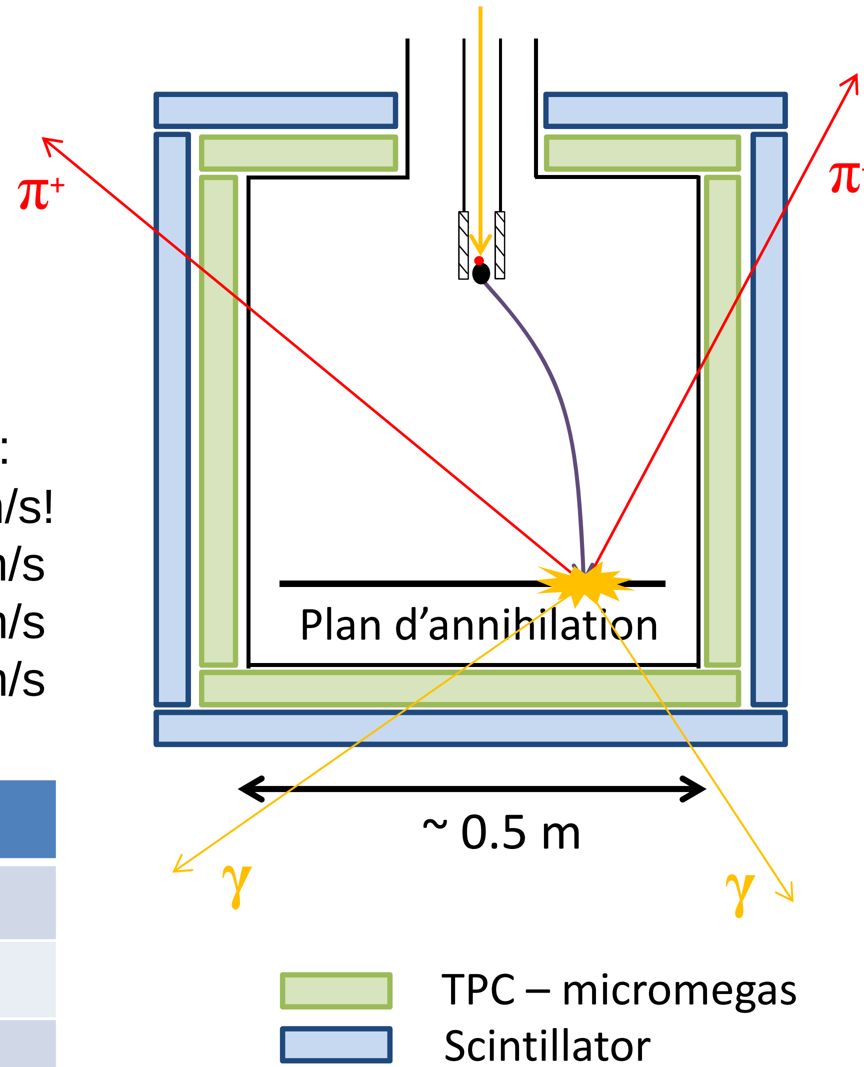
GBAR Schematic



The ultimate (drop) step



$$y = y_0 + v_0 t + \tfrac{1}{2} g t^2$$



Room temperature $\bar{p}$ ion:

8000 km/h →	2200	m/s!
4K H ions:	500	m/s
100 uK:	1	m/s
1 uK:	0.1	m/s

<u>For 1 $\bar{H}^+$:</u>

Need 10^7 $\bar{p}$

10^{12} Ps/cm^2

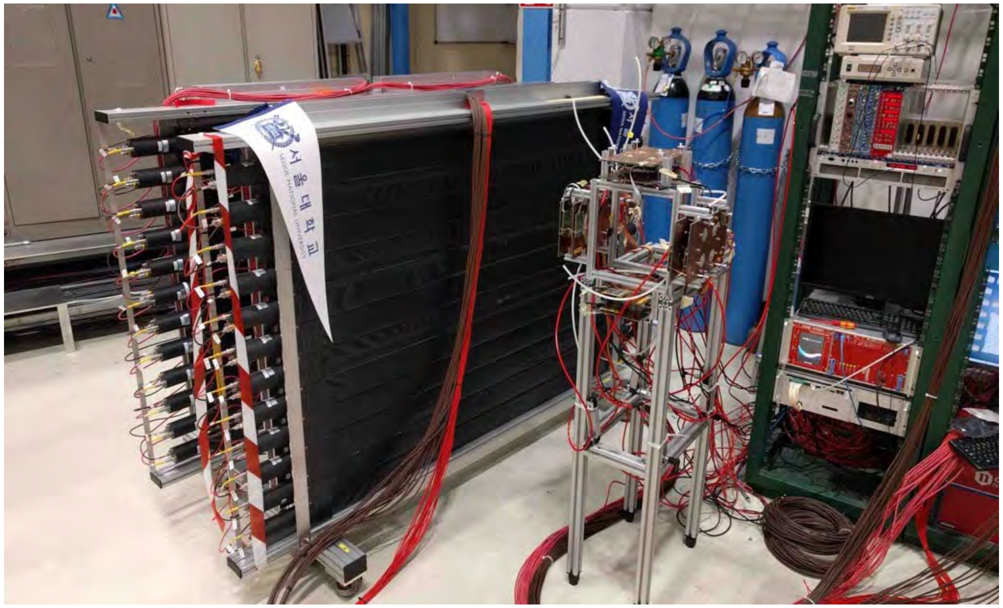
(10^{10} e^+)

in 1 ADE cycle

(110 s)

$\bar{H}$ ions (10 μK)	$\Delta g/g$
10^3	0.02
10^4	0.006
5 x 10^5	0.001

Detection: time of flight and tracking

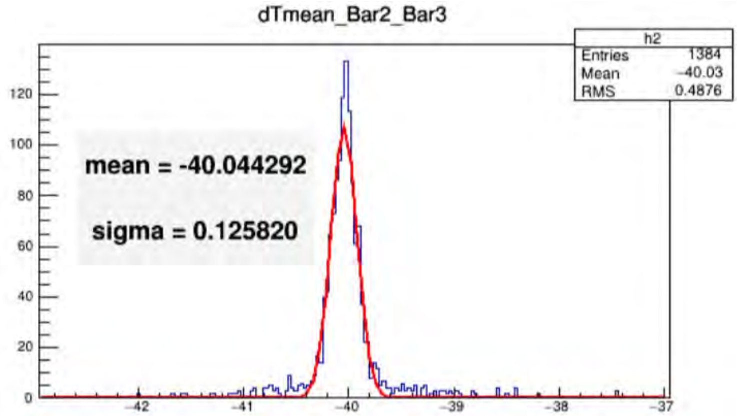


TOF planes
170 cm × 10cm × 5cm

test micromegas tracker

S.K. Kim and team
(Seoul National University)

P. Crivelli and team (ETH)
B. Vallage, S. Procureur & team (IRFU)



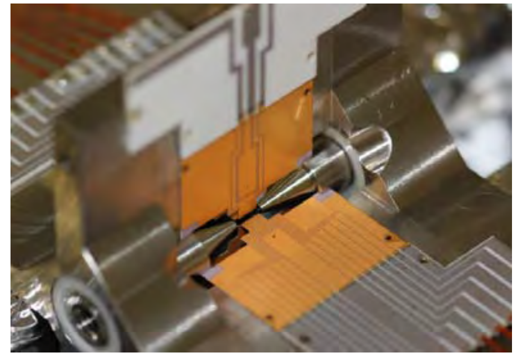
→80 ps resolution
allows to distinguish up-down particles

Test micromegas from ETHZ (x5 multiplexing)
19 planes 50 cm x 50 cm from Irfu and ETHZ
tested successfully with DREAM electronics

Aim: 1-mm vertex reconstruction accuracy

Sympathetic cooling of trapped $\overline{\mathrm{H}}^{+}$ ions

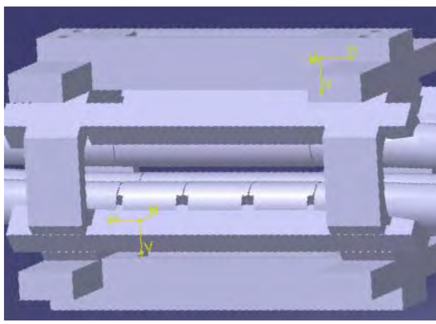
No transition to laser cool $\overline{\mathrm{H}}$
→ sympathetic cooling
transitions known for ^{9}Be
But Δm with ^{1}H still large



precision (56-MHz) μtrap

large capture trap

injection



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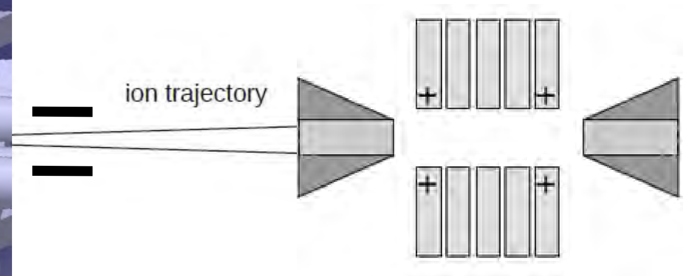
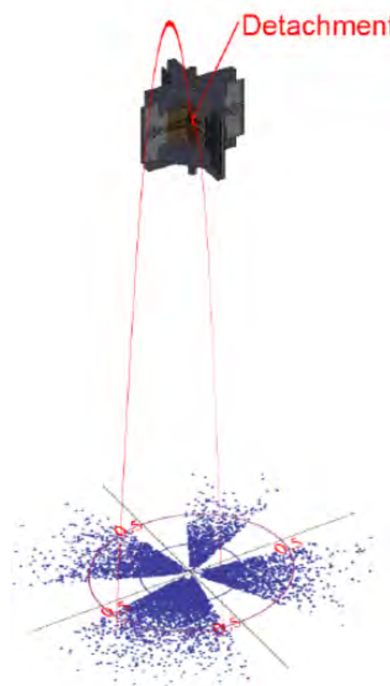
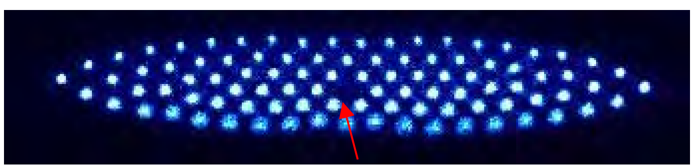
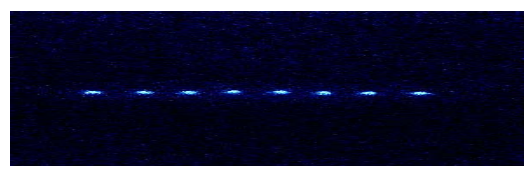






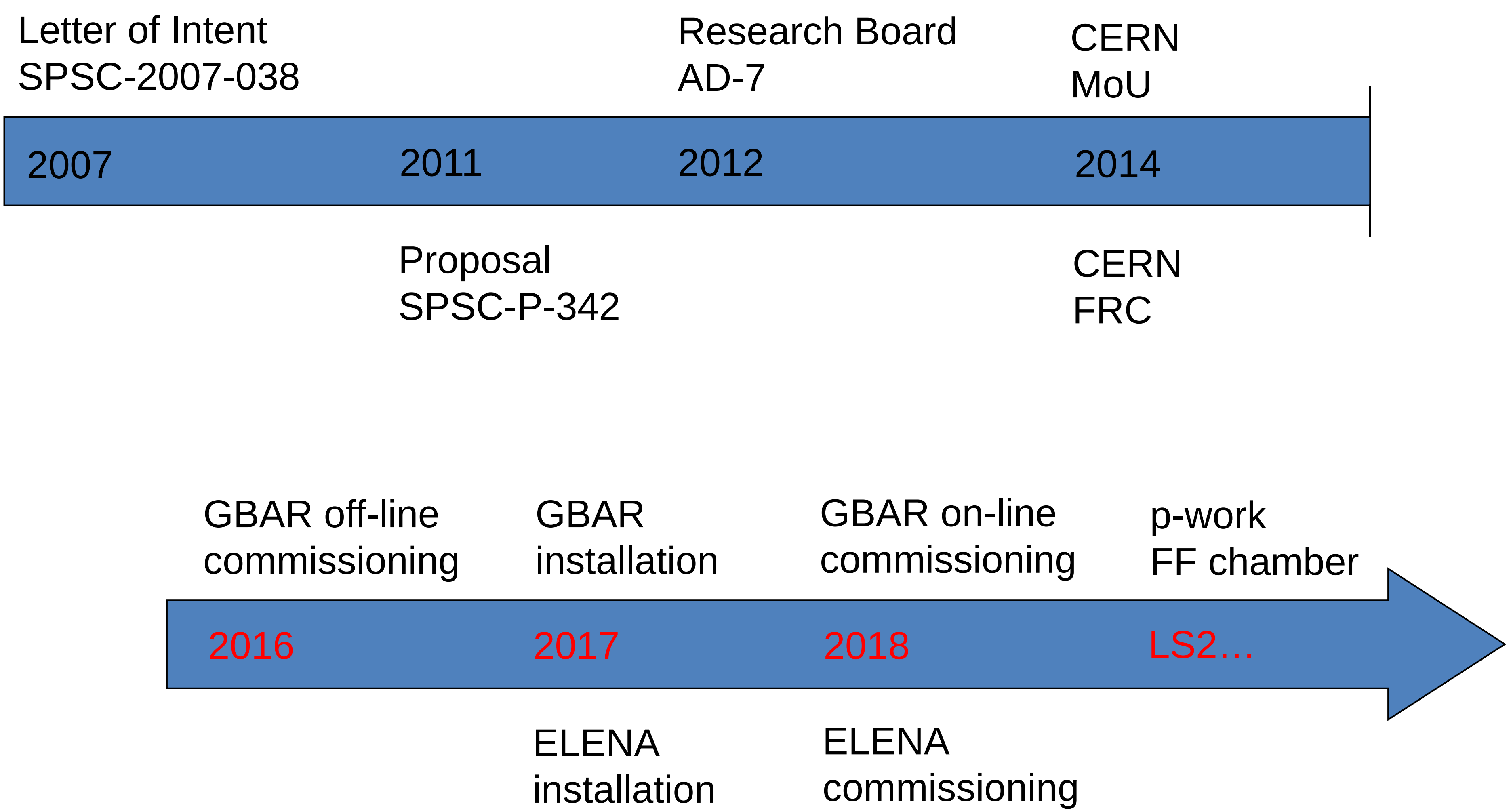
dark ion in capture trap (H_2^+ or H_3^+)
L. Hilico, J.-Ph. Karr et al. (LKB-Paris)



First results (using Ca ions)
S. Wolf, F. Schmidt-Kaler (Mainz)

$\overline{\mathrm{H}}^{+}$ cooled by Be “ice cubes”

GBAR Timeline



DOSSIER
Cosmologie

EXPÉRIENCE

Gbar va traquer le comportement de l'antihydrogène

❶ **Point d'arrivée des ions d'antihydrogène,** (un atome d'antihydrogène accompagné d'un positon).

❷ **Un tir laser chasse le positon.** Reste alors un atome d'antihydrogène.

❸ **L'atome d'antihydrogène** entame alors sa chute libre sur 20 cm.

❹ **L'antihydrogène percute le sol :** il y a annihilation comme à chaque fois que matière et antimatière se rencontrent.

❺ **Les particules produites** lors de cette annihilation parviennent aux détecteurs qui entourent la cuve. Leur identification permet de reconstituer la manière dont l'antihydrogène a chuté : cela revient en quelque sorte à peser l'antimatière.

CEA IRFU DESIGN IDÉES FRAÎCHES

Pour entreprendre des expériences sur l'antimatière, il faut ruser. L'antihydrogène tout comme l'hydrogène sont des atomes neutres, difficiles à manipuler. Au contraire d'une particule dotée d'une charge électrique qui, elle se met d'emblée en mouvement dans un champ électromagnétique. L'astuce ici, pour Gbar, est de fabriquer d'abord des ions antihydrogène, c'est-à-dire un atome d'antihydrogène affublé d'un positon. Ce dernier porte une charge positive, là où celle de l'électron est négative. L'ion antihydrogène peut être ainsi facilement acheminé à l'intérieur de la cuve ❶. Puis, un faisceau laser ❷ vient ôter le positon superflu, l'antihydrogène se retrouve seul dans la cuve. Sa chute peut commencer ❸. Lorsqu'il percute le plancher ❹, il s'annihile en créant de nouvelles particules. La cuve est entourée de détecteurs capables d'identifier les particules résultantes et ainsi de reconstituer la chute de l'antihydrogène. Rien ne présage qu'elle soit similaire à celle de l'atome d'hydrogène ❺. La moindre différence de comportement — une déviation de 1 % par exemple — permet de valider des hypothèses sur la nature de l'antimatière.

La quête récente des antiparticules

1932 — Découverte
Un an après sa prédiction théorique par Paul Dirac, Carl Anderson observe le positon (anti-électron).

1995 — Lear
Neuf atomes d'antihydrogène sont isolés pour la première fois dans l'anneau du Lear, au Cern.

2002 — Athena
Cette expérience parvient à produire 50 000 atomes d'antihydrogène de basse énergie.

2011 — Alpha
Les atomes d'antihydrogène sont stabilisés pendant plus de 16 minutes.

2016 — Gbar
L'antimatière chute-t-elle comme la matière ? Gbar va tenter d'y répondre.

SPL/COSMOS SPL/COSMOS CERN CERN CERN

N° 836 - Octobre 2016 - Sciences et Avenir - 33

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NEWS · 20 FEBRUARY 2018 · CORRECTION 20 FEBRUARY 2018

Physicists plan antimatter's first outing — in a van

Researchers intend to transport the elusive material between labs and use it to study the strange behaviour of rare radioactive nuclei.

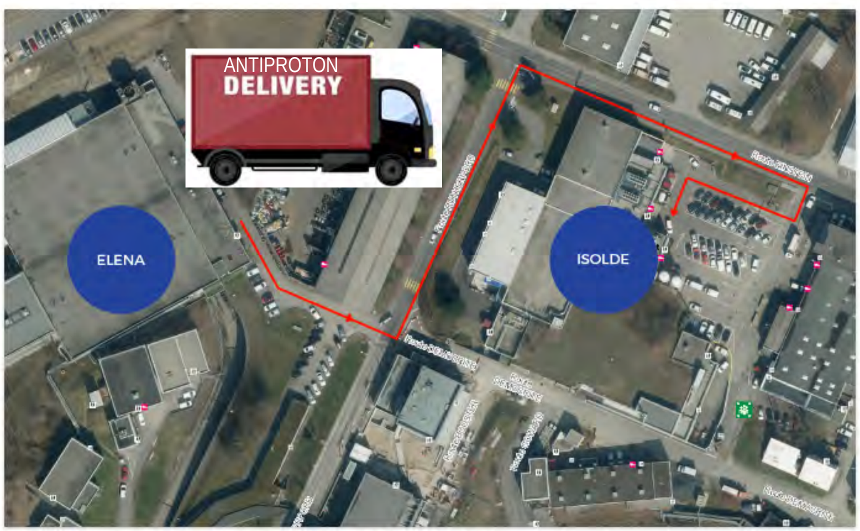
Elizabeth Gibney

CERN

Projet PUMA : l'antimatière prend la route

Un nouveau projet européen associant ELENA et ISOLDE va piéger l'antimatière afin d'explorer les phénomènes quantiques dans les noyaux radioactifs.

11 MARS, 2018 | Par Cristina Agrigoroae



Le voyage de l'antimatière entre les installations ELENA et ISOLDE (Image: CERN)

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NATURE | NEWS FEATURE

The race to reveal antimatter's secrets

In the shadow of the Large Hadron Collider, six teams are competing to answer one of the Universe's deepest existential questions.

Elizabeth Gibney

02 August 2017

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Maximilien Brice/CERN

A laboratory at CERN hosts the only usable source of antiprotons, the proton's antimatter counterpart.

PUMA: A. Obertelli and team (TU-Darmstadt)

antimatter in the (social) media

Au Grand Rex (mais pas tout à fait live du CERN…)

Summary

LE CERN ACTUALITÉS SCIENCE RESSOURCES RECHERCHER

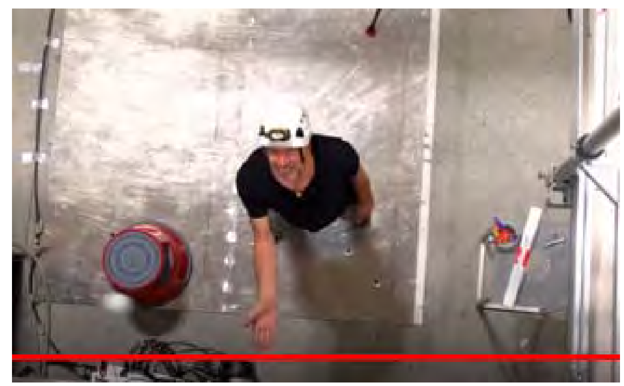
De nouvelles expériences sur la gravité au CERN

Les expériences ALPHA-g et GBAR ont reçu leurs premiers faisceaux d'antiprotons

2 NOVEMBRE, 2018 | Par Ana Lopes

L'installation de l'expérience ALPHA-g dans le hall du Décélérateur d'antiprotons, au CERN. (Image: CERN)

ANR POSITRAP (2011-2014)
ANR ANTION (2014-2018)
(enfin) Projet IN2P3



- ❖ Interesting physics goal – lots of competition!
- ❖ First experiment to receive ELENA antiproton beam
- ❖ GBAR attempted antihydrogen fabrication in 2018
- ❖ 2 PhD theses from CSNSM (P. Grandemange, 2013 & A. Husson, 2018)
- ❖ LS2 plans: matter-analog reaction measurements & remaining installation
- ❖ Long-term experiment!

GBAR Collaboration – 53 scientists/17 institutes

CSNSM
IPCMS
東京大学 THE UNIVERSITY OF TOKYO
Swansea University School of Physical Sciences
東京理科大学 Tokyo University of Science
ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich
RIKEN

Irfu
UPPSALA UNIVERSITET
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ
Laboratoire Kastler Brossel Physique quantique et applications
P.N.Lebedev Physical Institute of the Russian Academy of Science
ill NEUTRONS FOR SCIENCE® Institut Laue-Langevin

P. Pérez (IRFU), Spokesperson

M. Charlton, J. Choi, M. Chung, P. Cladé, P. Comini, P. Crivelli, P-P. Crépin, O. Dalkarov, P. Debu, L. Dodd, A. Douillet, S. Guellati, J. Heinrich, P-A. Hervieux, A. Husson, P. Indelicato, G. Janka, S. Jonsell, J-P. Karr, K. Khabarova, B. Kim, E-S. Kim, S. Kim, Y. Ko, N. Kolachevski, T. Kosinsky, N. Kuroda, B. Latacz, H. Lee, J. Lee, A. Leite, E. Lim, L. Liszkay, T. Louvradoux, D. Lunney, K. Lévêque, G. Manfredi, B. Mansoulié, M. Matusiak, G. Mornacchi, V.V. Nesvizhevsky, F. Nez, S. Niang, R. Nishi, S. Nourbaksh, K. Park, P. Pérez, B. Radics, C. Regenfus, S. Reynaud, J-Y. Roussé, A. Rubbia, J. Rzadkiewicz, Y. Sacquin, F. Schmidt-Kaler, N. Sillitoe, M. Staszczak, B. Vallage, D-P. van der Werf, A. Voronin, A. Welker, S. Wolf, D. Won, S. Wronka, Y. Yamazaki, K-H. Yoo

Thanks for listening!