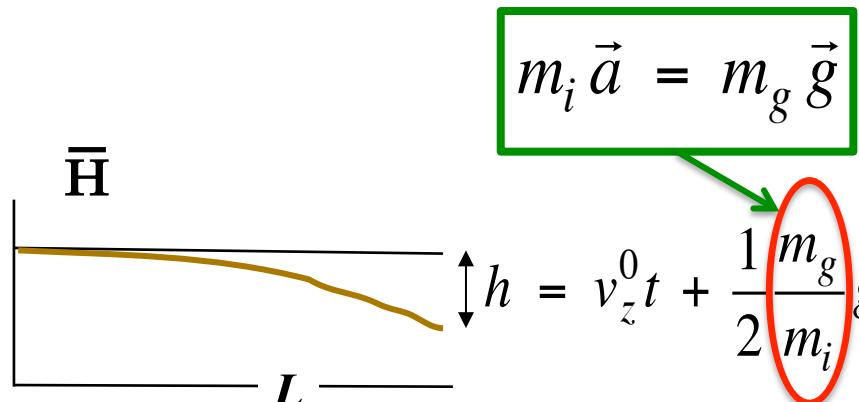
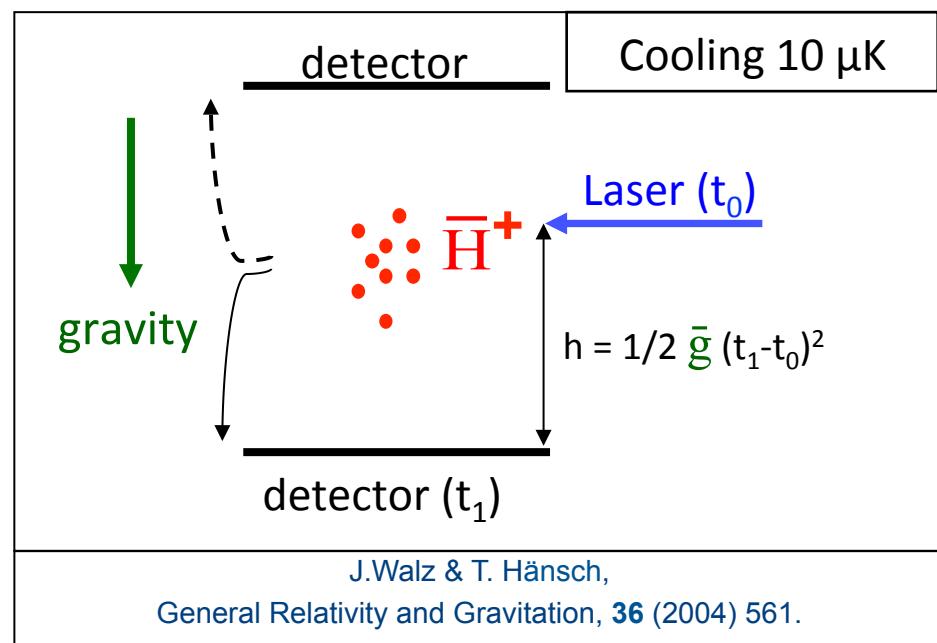


GBAR principle: cool \bar{H}^+ to get ultra-slow \bar{H}

- $\bar{H}^+ = \bar{p} e^+ e^+$
- Sympathetic cooling with $Be^+ \rightarrow 10 \mu K$
- Photodetachment of e^+
- Time of flight



L 0.1 m

h 10 cm

Δt 143 ms

v_h 0.5 m/s

T_H 20 $\mu K \sim 7$ neV

Goal

$$\frac{\Delta g}{g} \leq 1\%$$

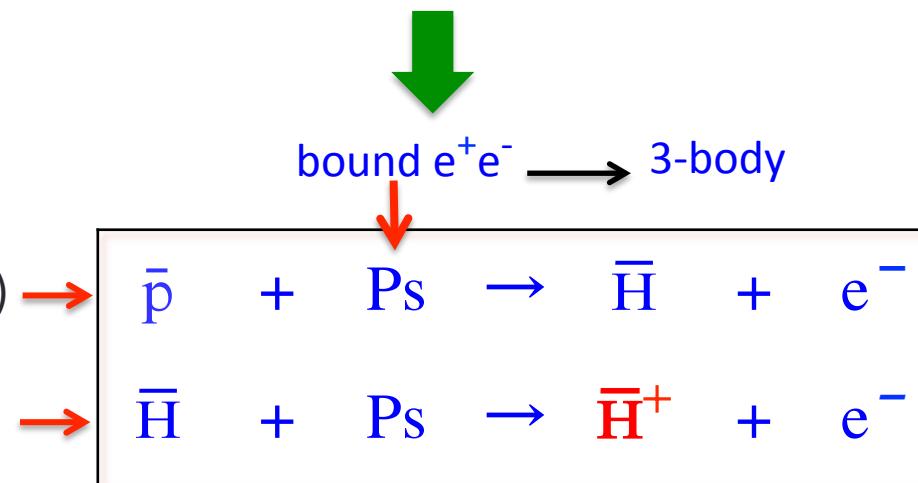
A recipe to produce anti ions

Standard \bar{H}
production
via 3-body process



demonstrated by ATRAP (2004)

Idea for GBAR:
2nd charge exchange reaction



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

Binding energy of \bar{H}^+ = 0.75 eV = energy level of Ps
(n=3)



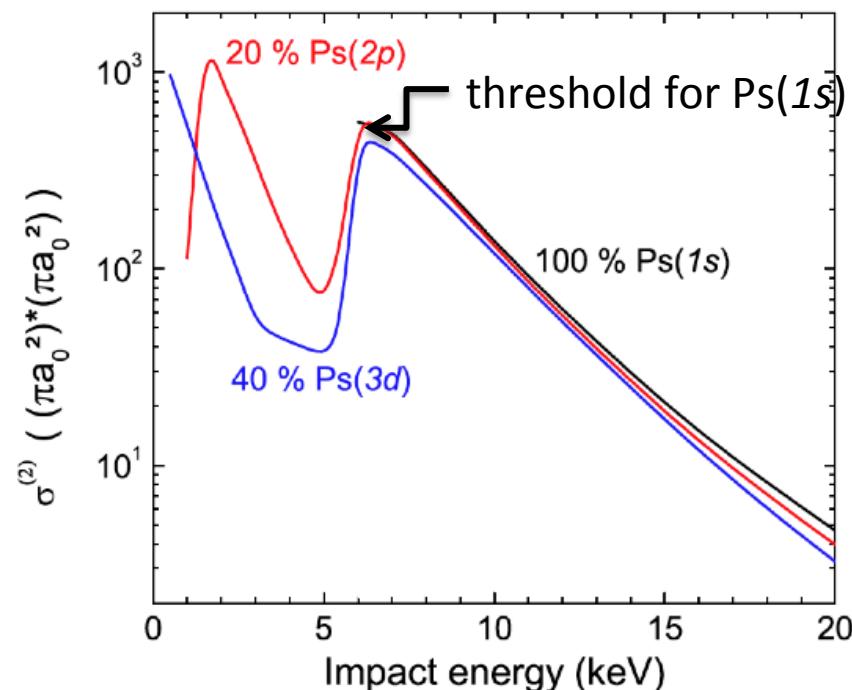
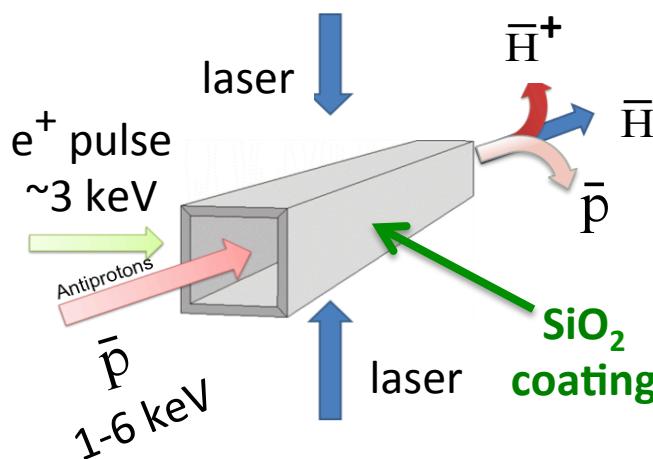
Expect cross-section enhancement if Ps excited to n=3

\bar{H}^+ production

CERN provides per bunch every 110 s

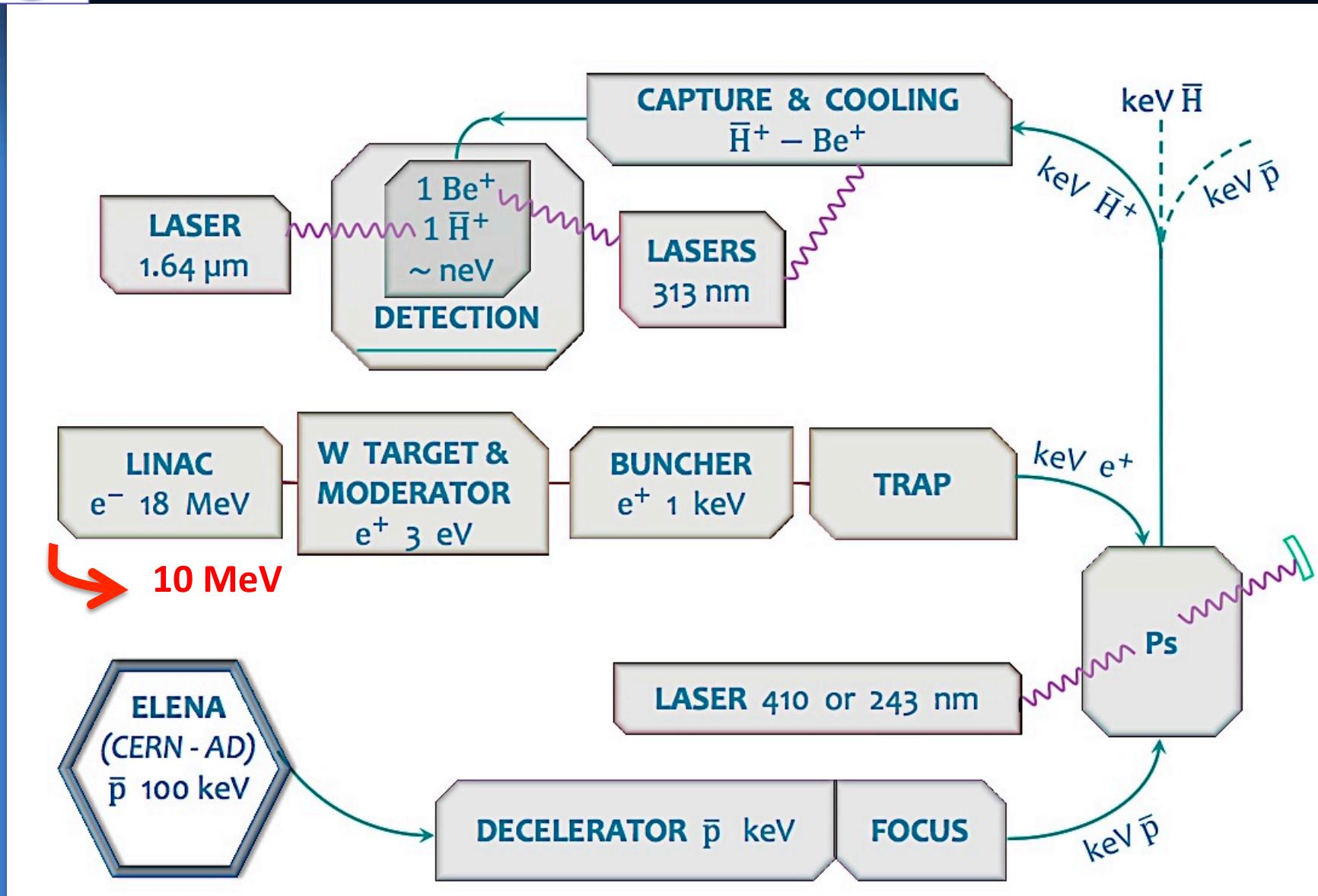


$$\begin{array}{c} \sim 0.5 \cdot 10^7 \bar{p} \\ 10^{12} P_S / \text{cm}^2 \end{array} \quad \left. \right\} \rightarrow \begin{array}{l} 10^4 \bar{H} \\ 1 \bar{H}^+ \end{array}$$



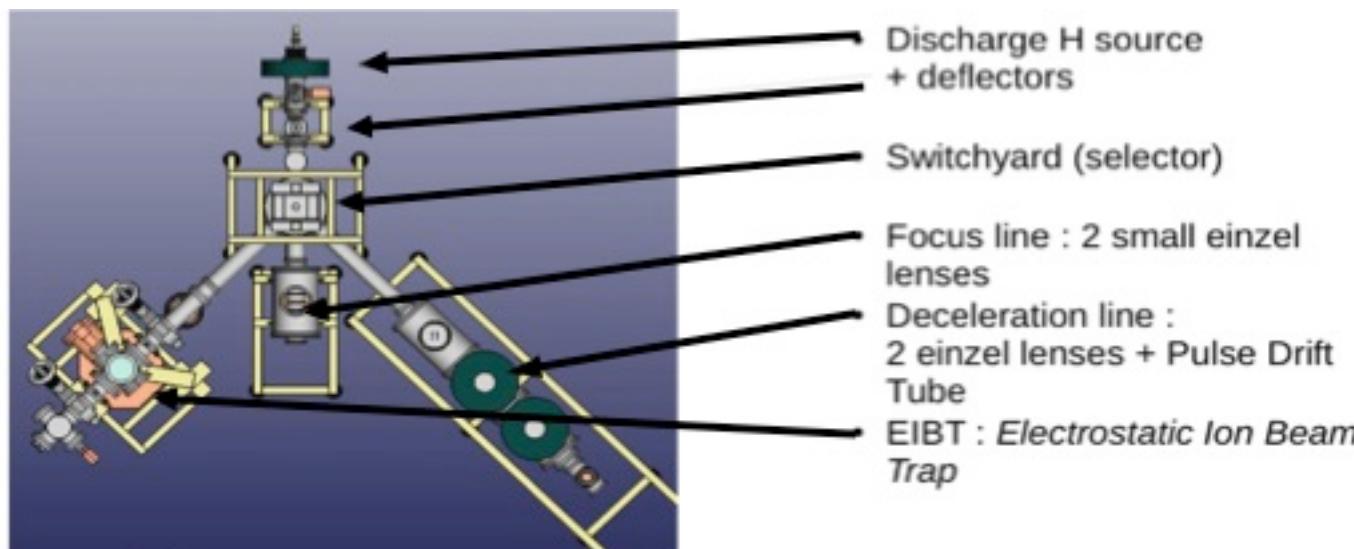
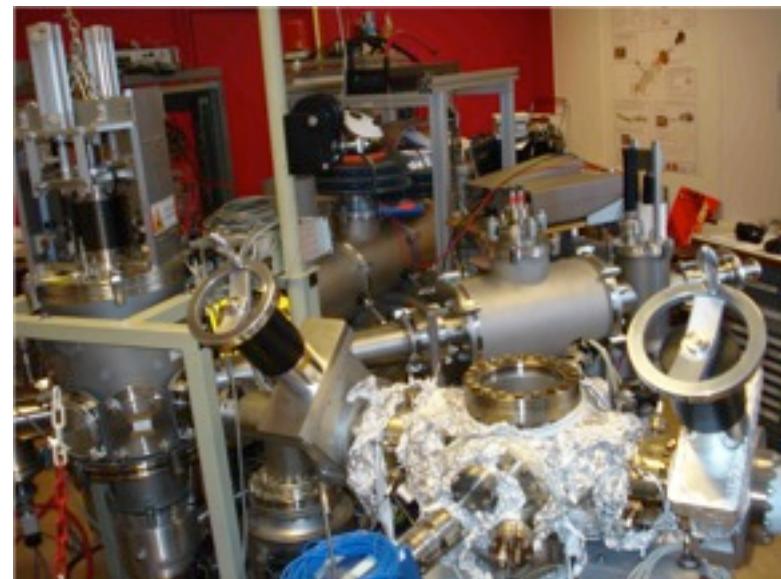
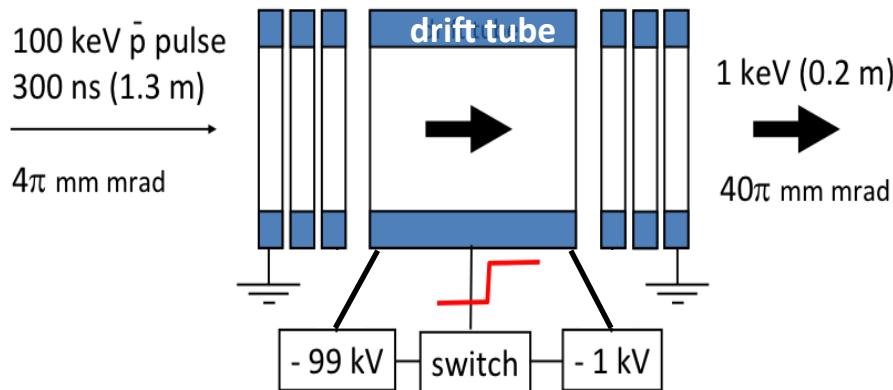
P. Comini and P-A. Hervieux, J. Phys.: Conf. Ser. 443, 012007 (2013)
P. Comini, P-A. Hervieux and F. Biraben, LEAP 2013

GBAR overall scheme



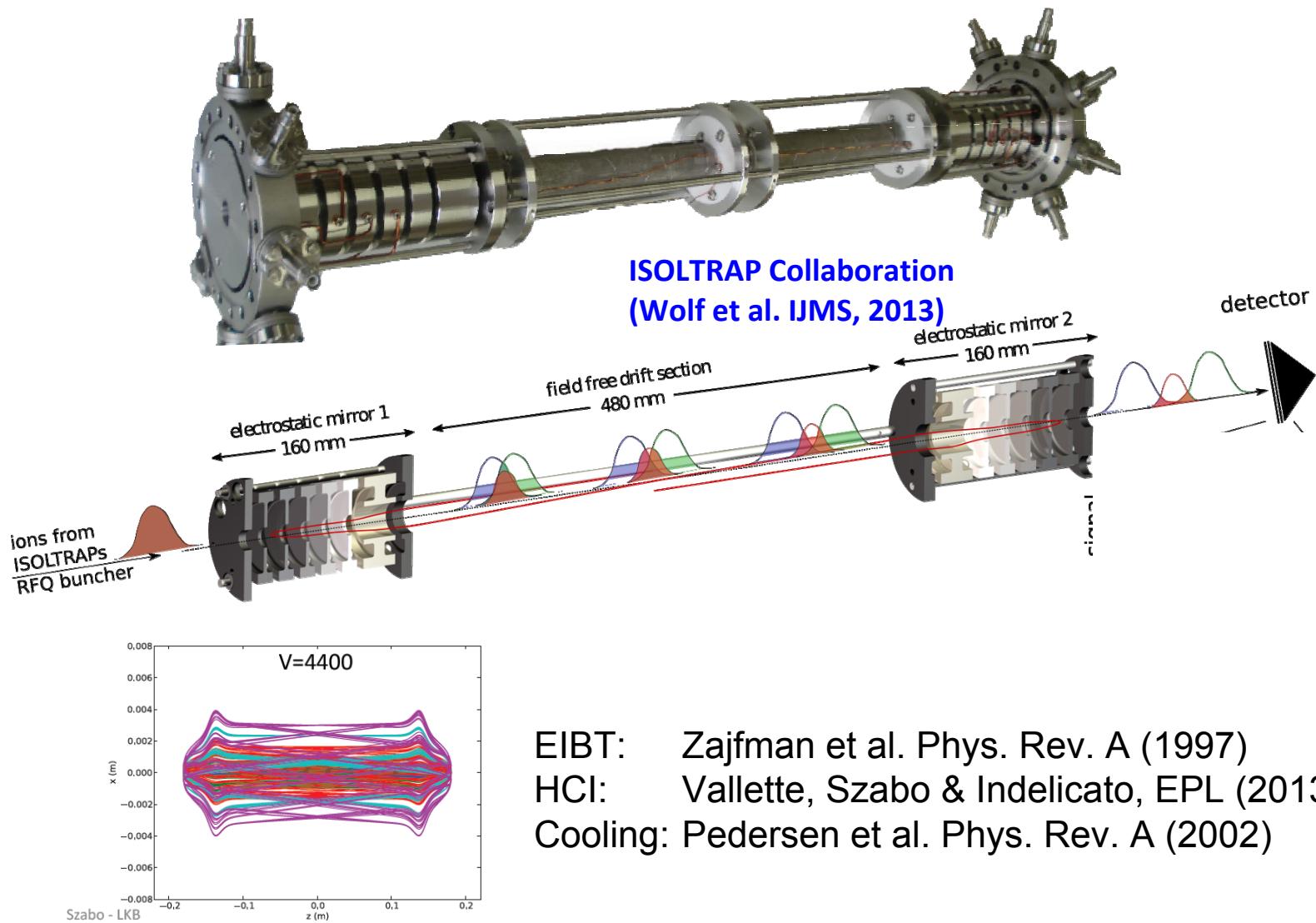
Proton/antiproton decelerator

D. Lunney
A. Husson



Multi-Reflection Time-of-Flight separator (Electrostatic Ion Beam Trap)

P. Indelicato, C. Szabo
P. Dupré, D. Lunney

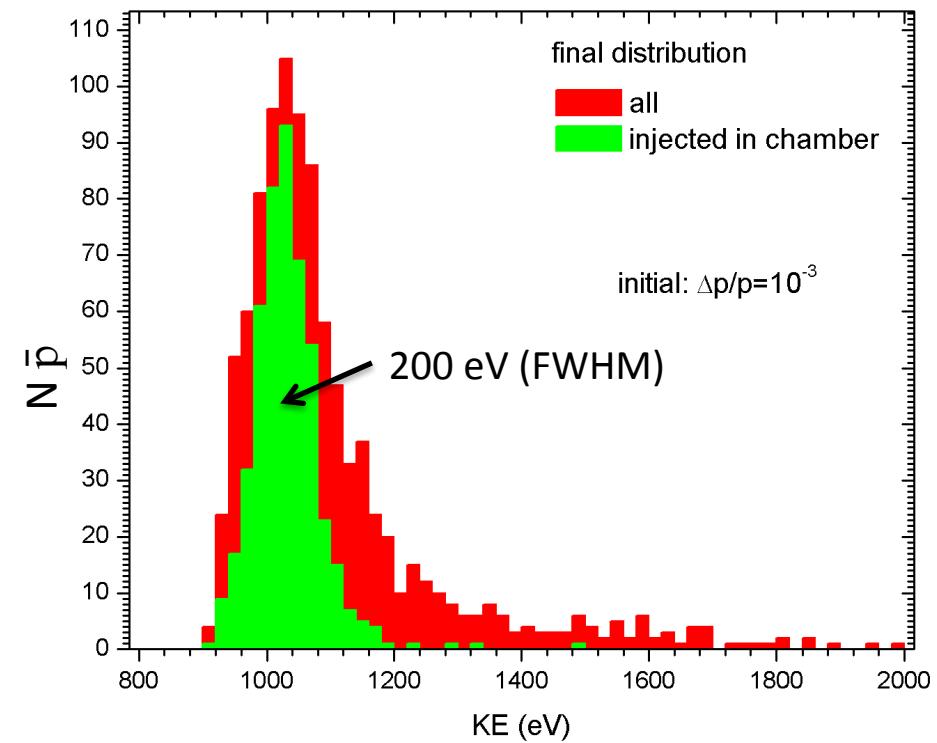
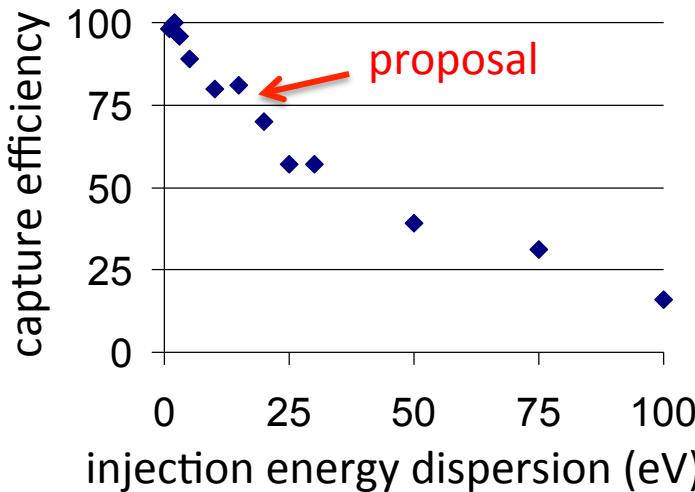


\bar{p} transport to reaction chamber

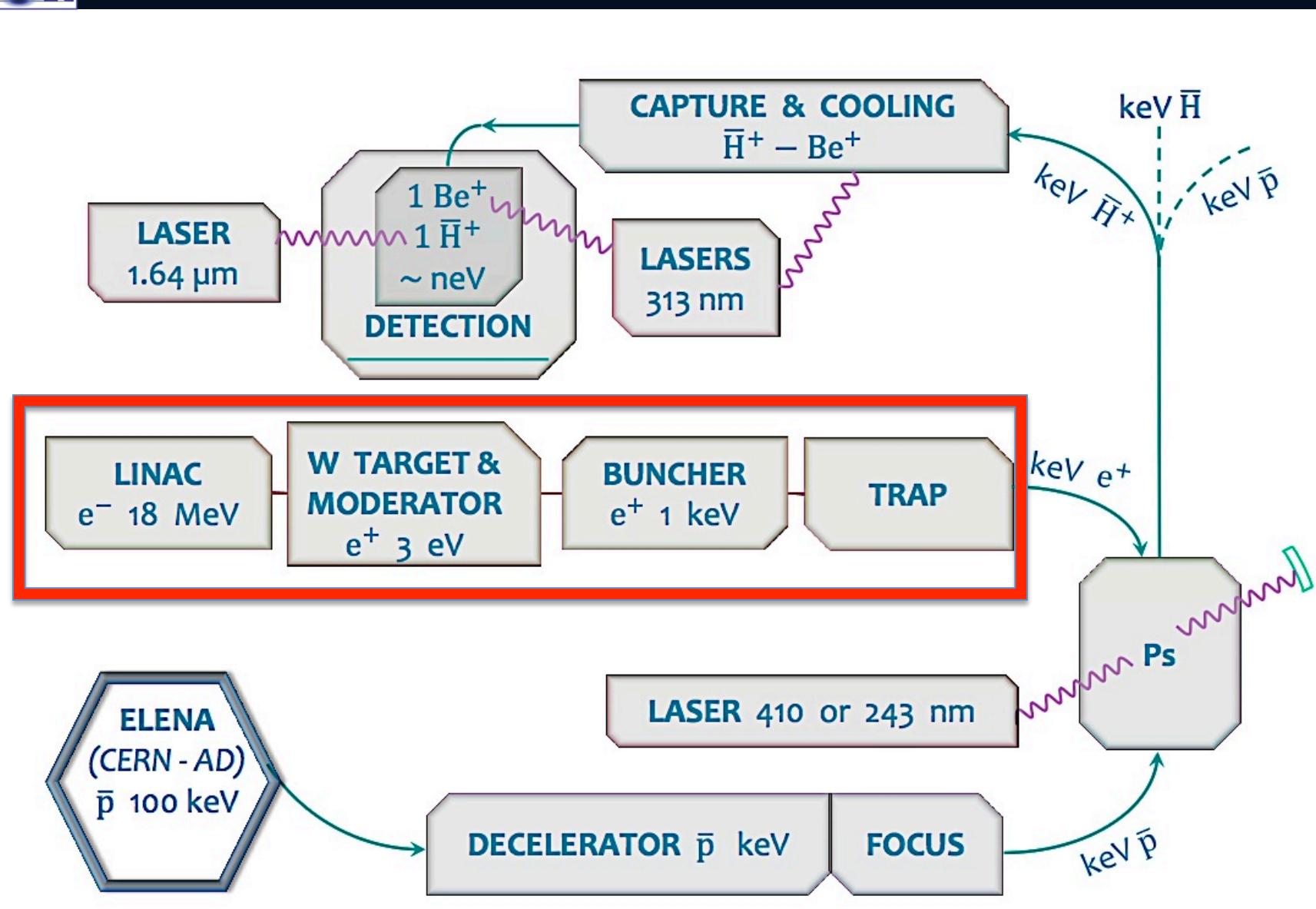
D. Lunney
P. Dupré

ELENA \bar{p} beam emittance = $4\pi \text{ mm mrad}$
decelerating beam to 1 keV → $40\pi \text{ mm mrad}$
acceptance of the 1-mm diameter, 20-mm long Ps target chamber = $25\pi \text{ mm mrad}$
decelerator optics → 33-38 % transmission through Ps target
decelerating beam to 6 keV → $16\pi \text{ mm mrad}$
transverse emittance orientation no problem (good matching with decel)

But, longitudinal momentum dispersion too large for \bar{H}^+ catching trap



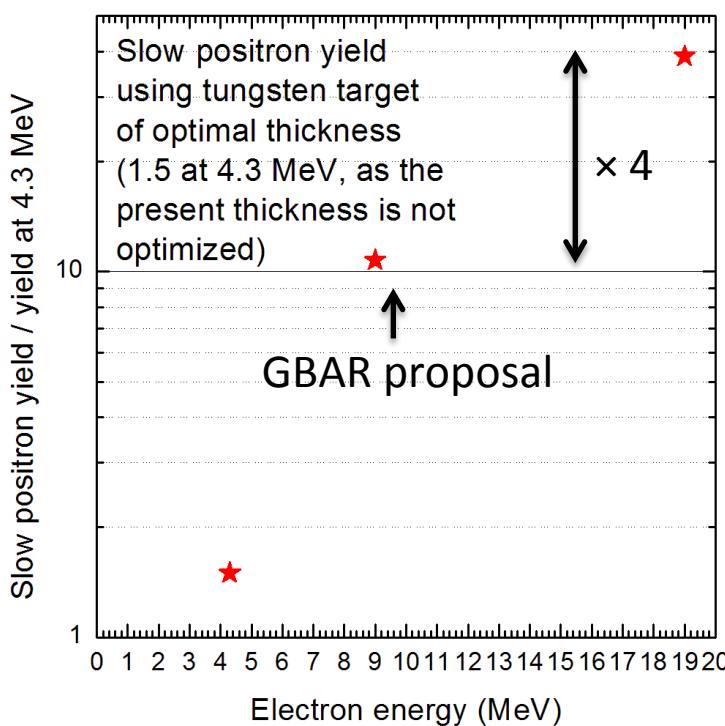
Positron production & accumulation



Slow e⁺ yield

fast e⁺ rate increases with electron energy

fast → slow e⁺ : efficiency decreases with incident fast e⁺ energy

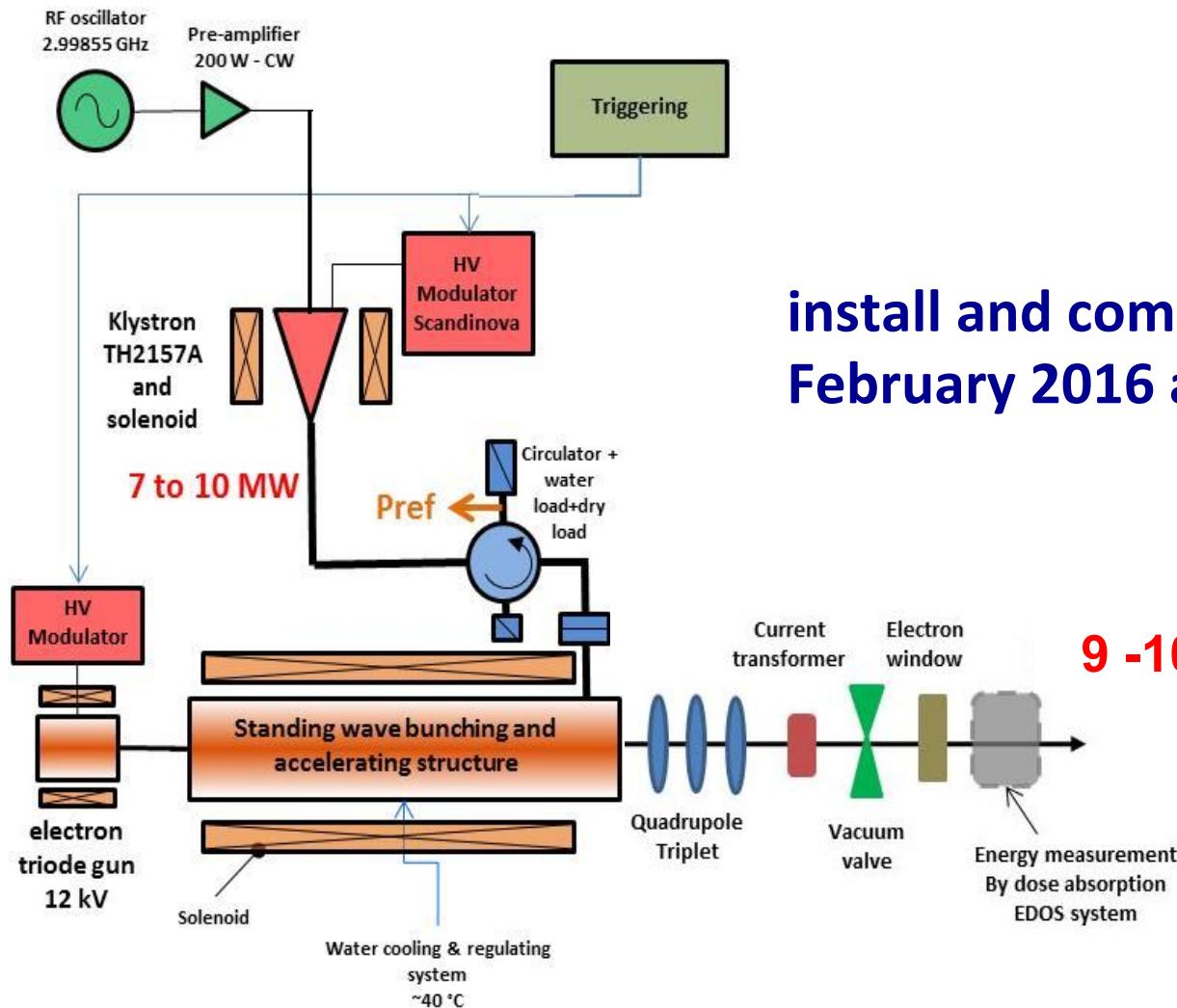


Parameter	Specification
Energy	10 → 20 MeV
Peak current	300 mA
Beam Pulse length	2 μ s
Repetition rate	300 Hz
Availability	24/24 h 7/7 days

Due to safety procedures must stay \leq 10 MeV

Final version of e⁻ Linac

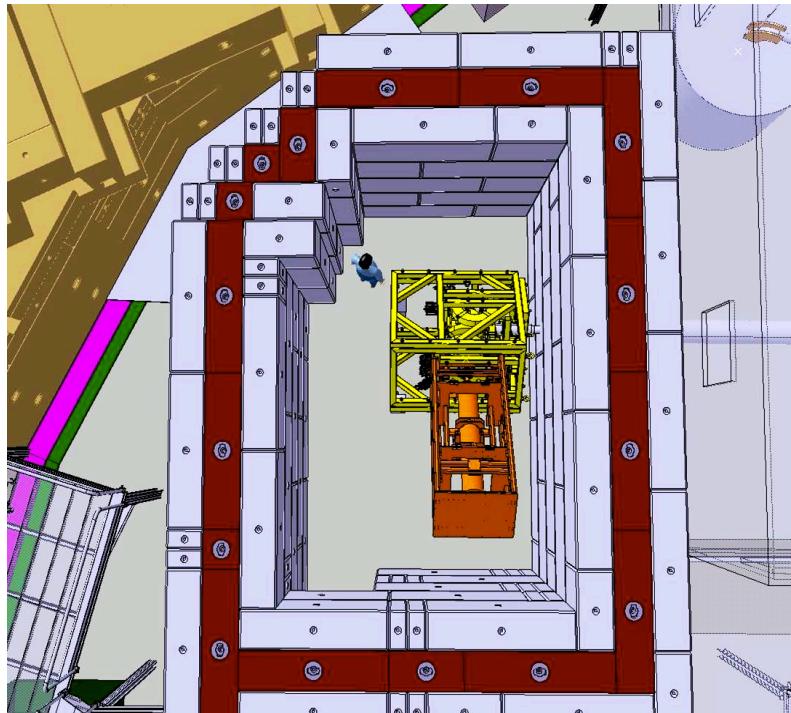
S. Wronka
P. Krawczyk



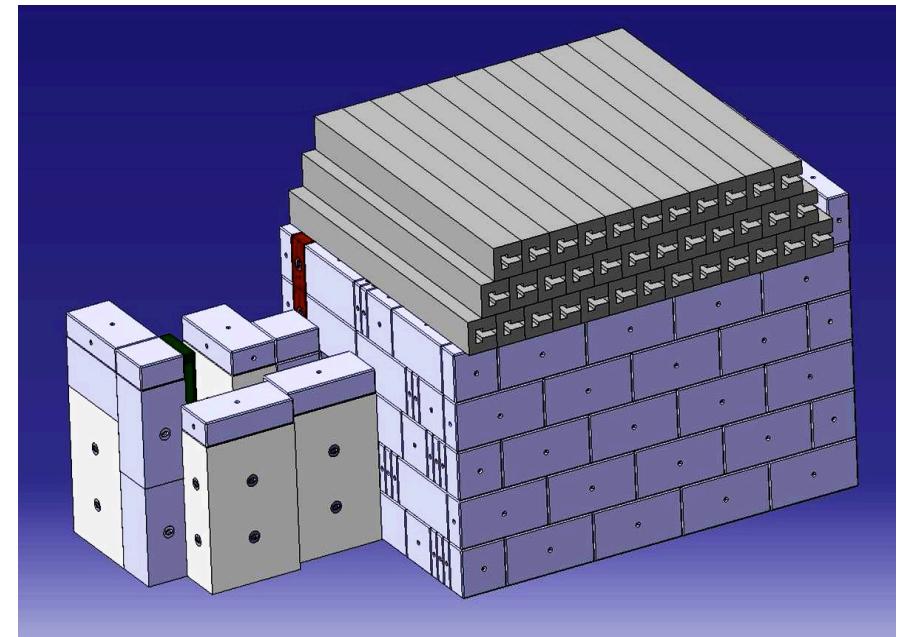
install and commission
February 2016 at CERN

First designs of Linac shielding

O. Choisnet
F. Butin CERN



120-160 cm thick shielding
Includes at least 40 cm iron
re-furbish LEP yokes

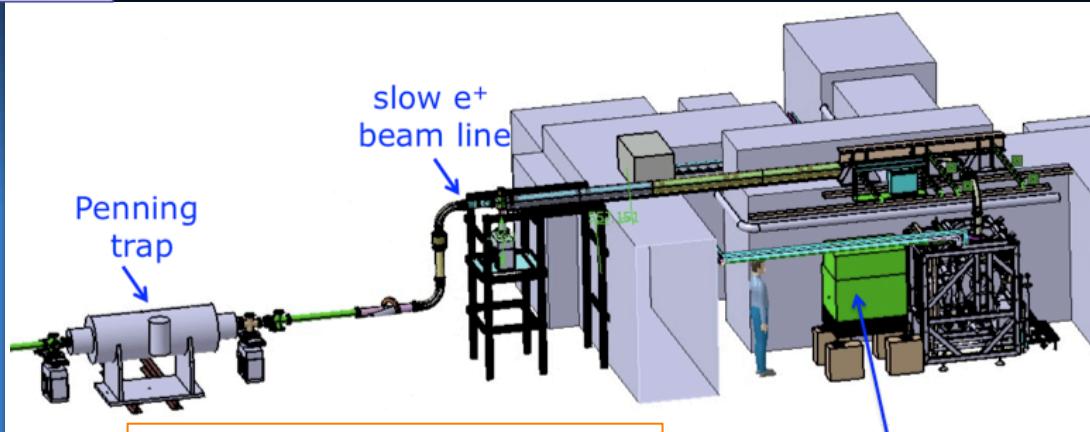


Weight might induce ground level shifts
in AD beam area!

Working on reducing Iron weight...

e^+ / Ps demonstrator at Saclay

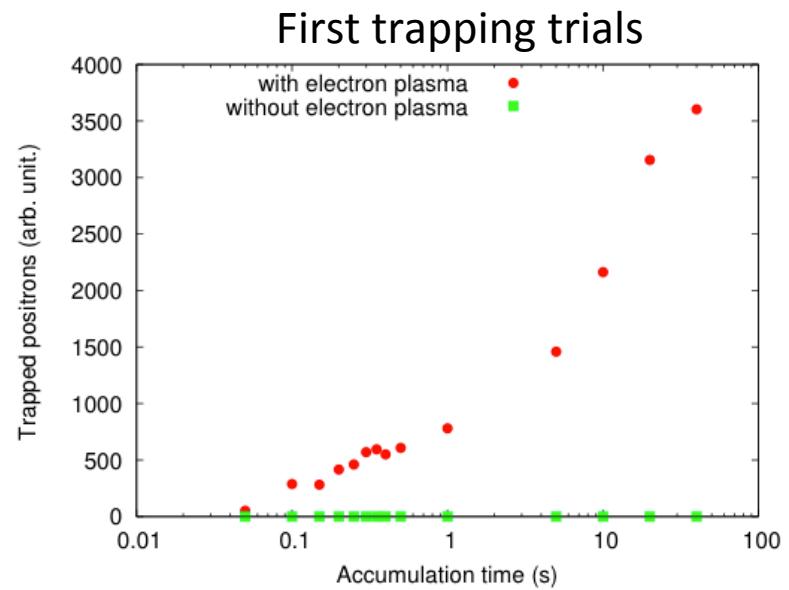
L. Liszkay
Y. Sacquin
D.P van der Werf



Secondary beam line
→ moderator developments
→ e^+ /Ps converters

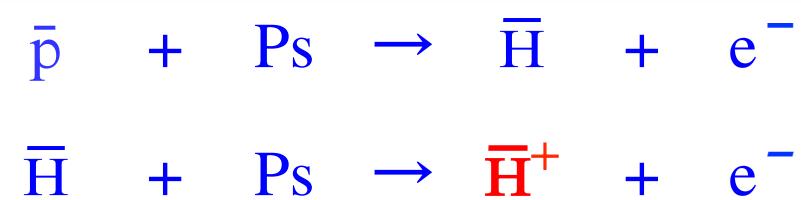
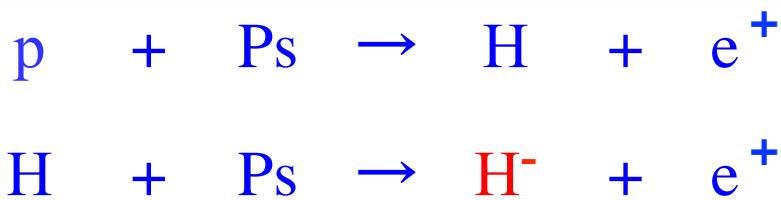


- 4.3 MeV / 200 Hz / 2.5 μ s / 120 μ A
- 3 10^6 slow e^+ /s
- with first W mesh moderator
- Ps* laser being prepared at LKB (Paris)



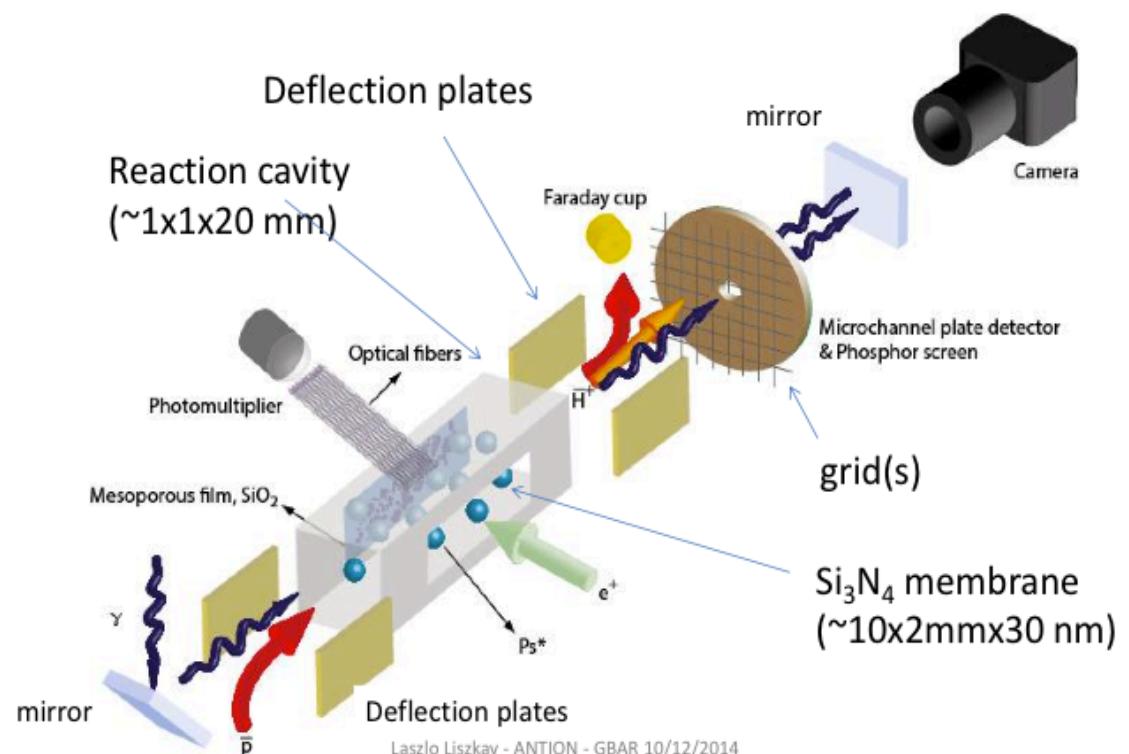
(anti) Ion Production

L. Liszkay
D. Lunney
F. Nez



ANR
funding

2015: protons at Saclay
2016: protons at CERN
2017: antiprotons

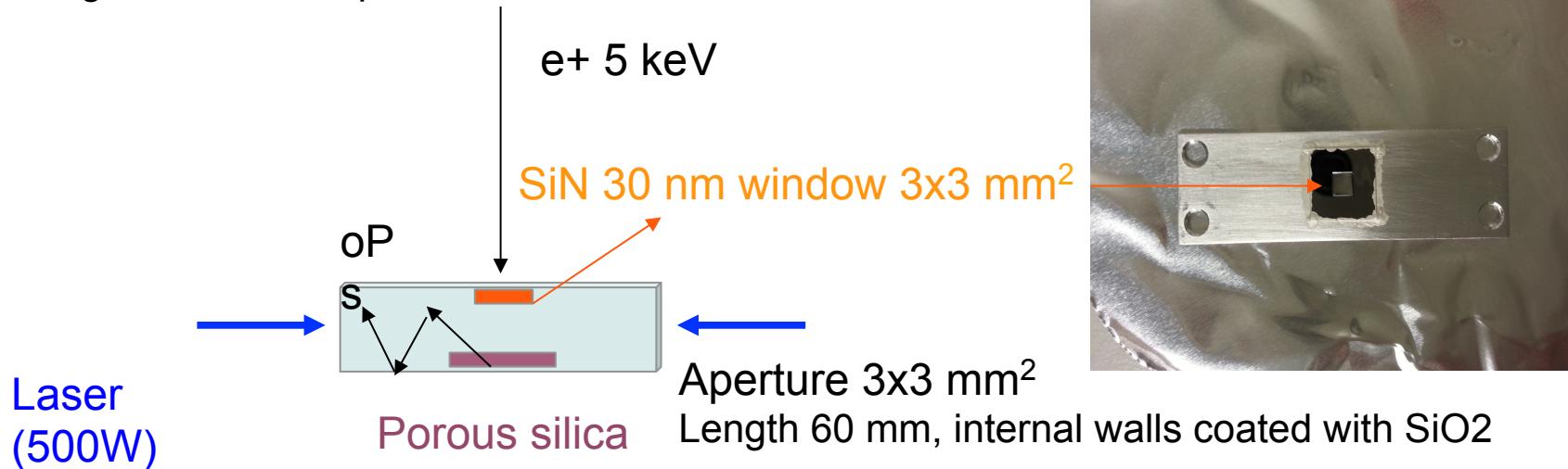


Ps 1S-2S experiment at ETHZ

P. Crivelli

P. Crivelli (ETHZ), D. Cooke (ETHZ), A. Antognini (ETHZ), K. Kirch (ETHZ/PSI), A. Rubbia (ETHZ), J. Alnis (MPQ), T. W. Haensch (MPQ), B. Brown (Marquette University)

enhance Ps interaction time with laser \leftarrow target in “tube” geometry
during its lifetime Ps passes about 10 times in the laser beam



SiN transmission @ 5 keV $\sim 100\%$, Ps fraction into vacuum of 15% (from 22%).

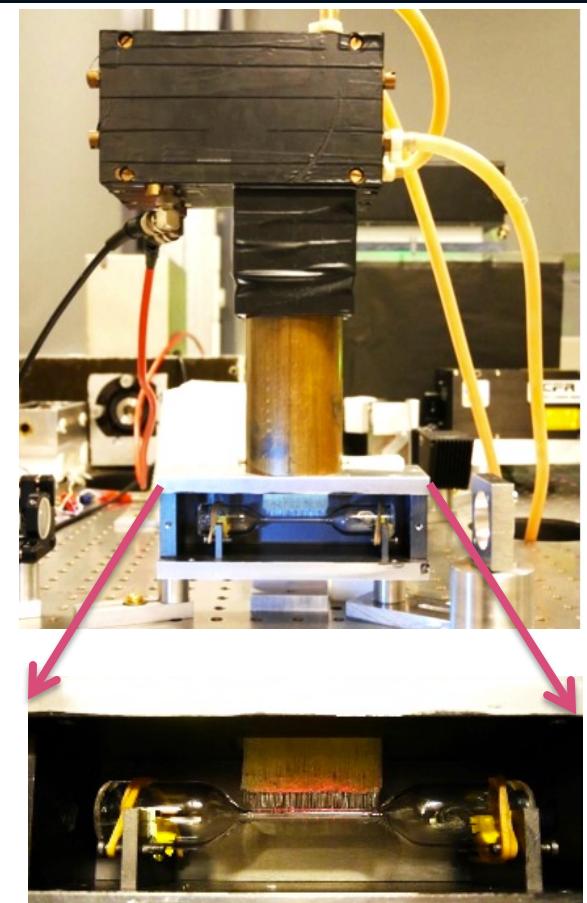
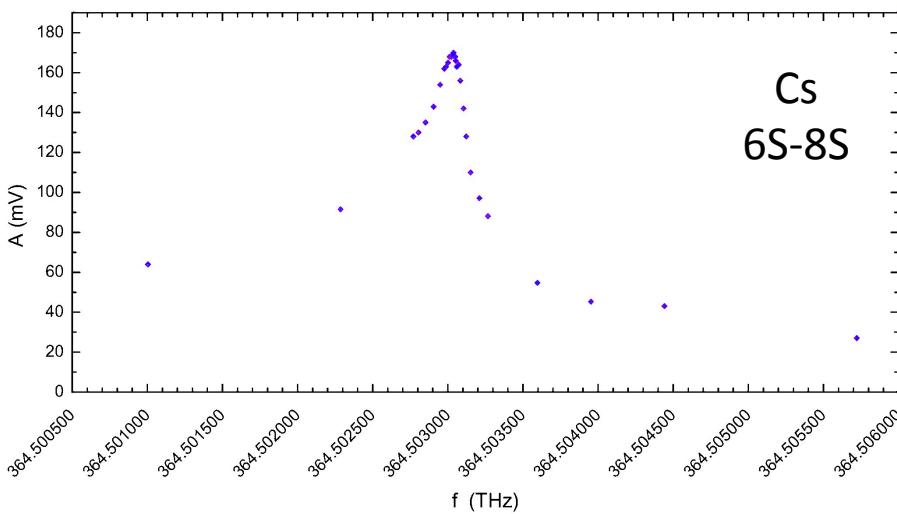
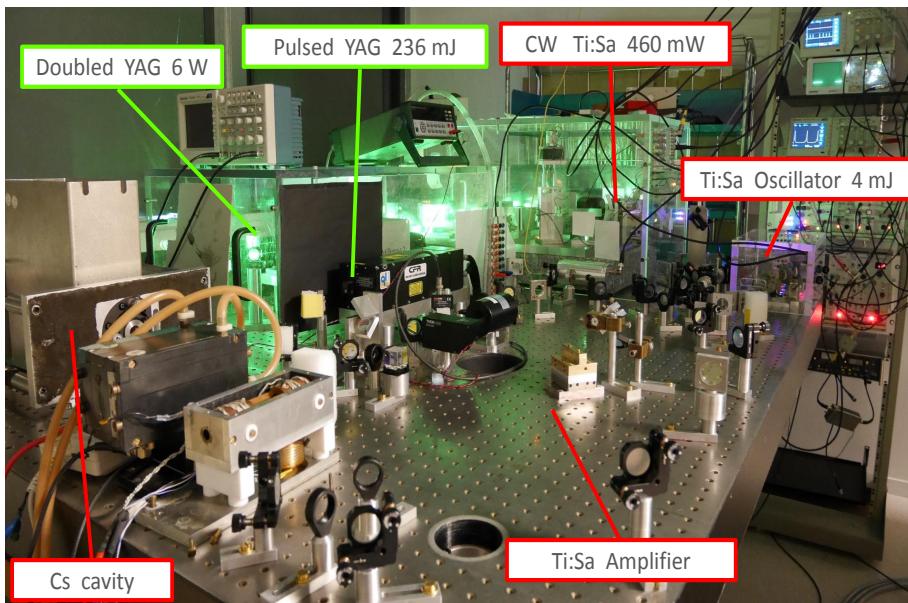
Ps lifetime is not reduced (no pick-off effect).

Losses: positron missing the target.

Number of detected Ps (2S) annihilations compatible with expected 0.4% de-excitation probability per collision via Stark mixing ($2\text{S} \rightarrow 2\text{P} \rightarrow 1\text{S}$) using calculated cross sections for this process: J. Mitroy, I. A. Ivanov, PRA 65, 012506 (2002)

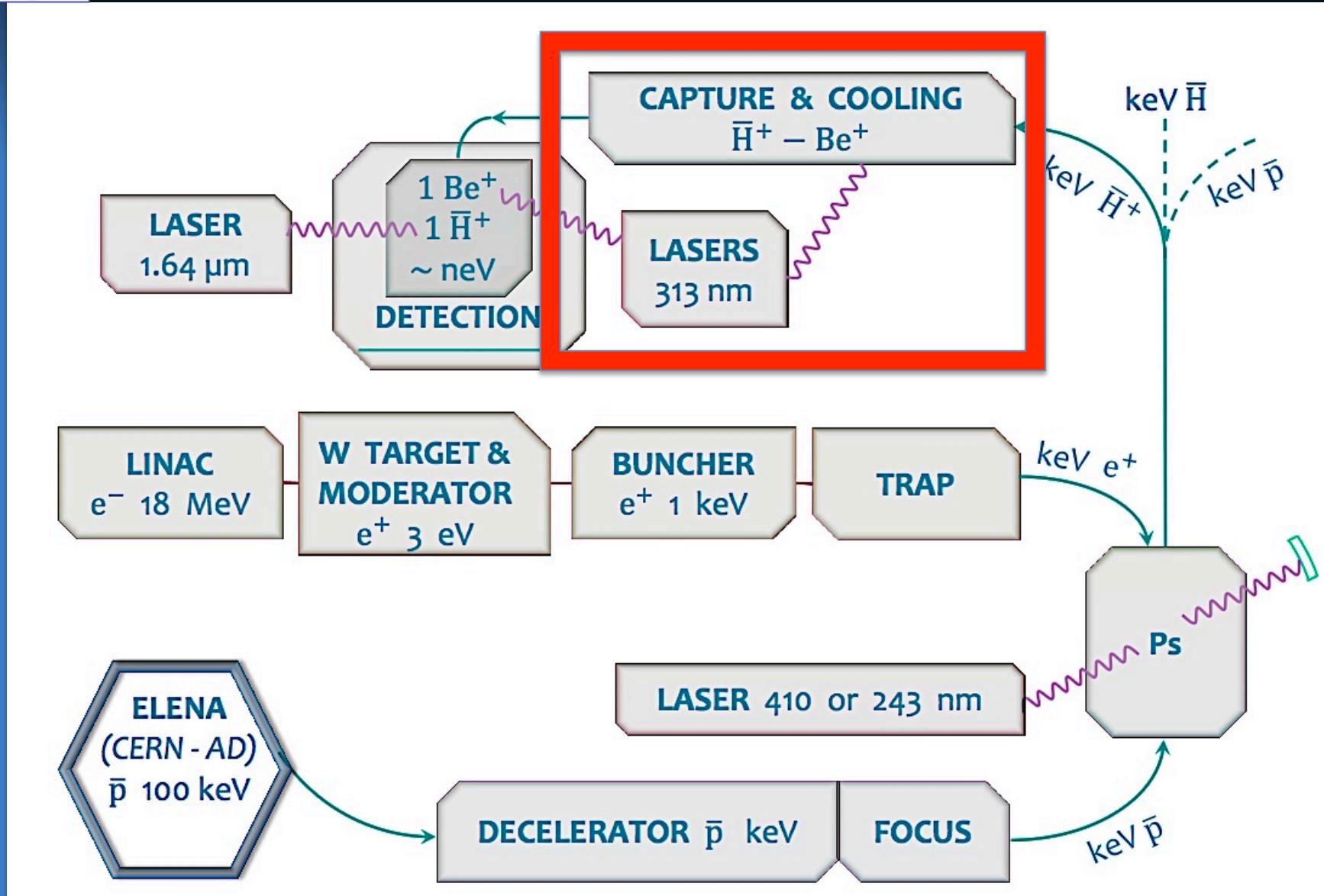
Ps excitation laser at LKB

F. Biraben
P. Comini
F. Nez



Cs cell with fiber optic bundle
conditions similar to Ps^*
→ ready for Ps^* measurements

\bar{H}^+ cooling

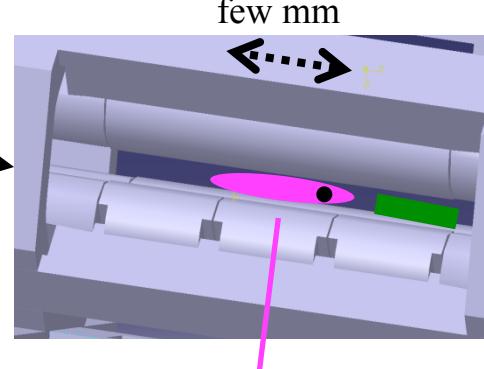
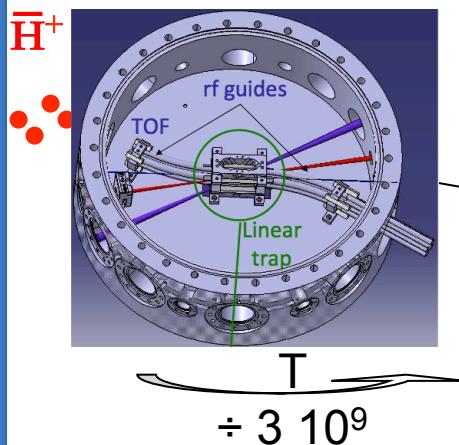


Two cooling steps

L. Hilico
F. Schmidt-Kaler

First step Capture and sympathetic Doppler cooling by laser cooled Be⁺ ions

in the linear **capture trap** (Paul trap, $r_0 = 3.5$ mm, $\Omega = 13$ MHz)



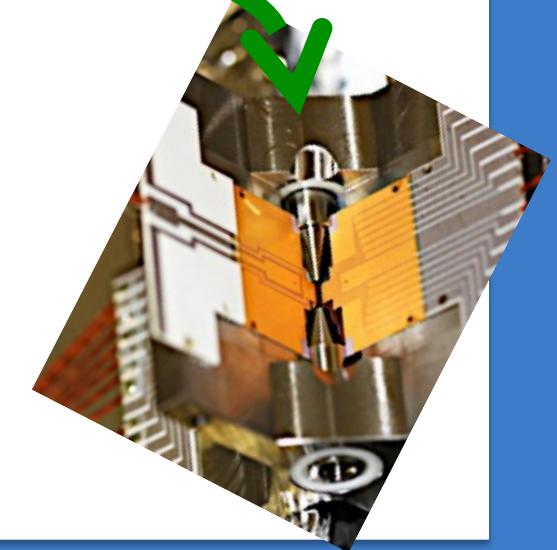
313 nm laser (1/2 ready)

> 10 000 laser cooled Be⁺ / HD⁺ ions
100 neV, T ~ mK

Second step

Transfer and ground state cooling
of a Be⁺/H⁺ ion pair in the **precision trap**

tests with H₂⁺ / H⁺ REMPI source
joint ANR and DFG grant



\bar{H}^+ cooling simulations

L. Hilico

9/1 mass ratio : bad mechanical coupling

9/2 mass ratio : much better mechanical coupling

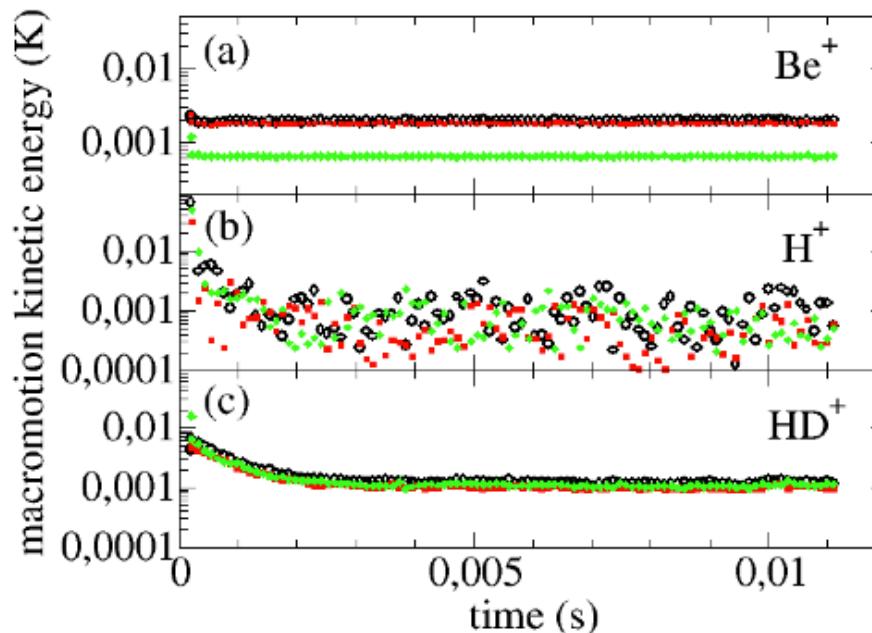
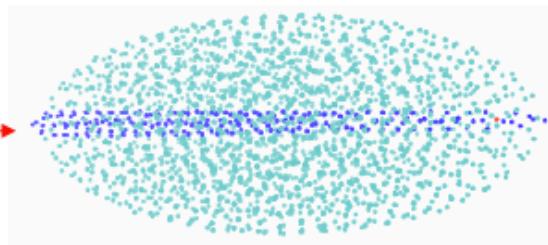
→ Idea : try an intermediate ion 9 / 3 / 1

C. B. Zhang, D. Oenberg, B. Roth, M. A. Wilson, and S. Schiller,
Phys. Rev. A 76, 012719 (2007).
L. Hilico et al., IJMPICS 2014

few meV \bar{H}^+

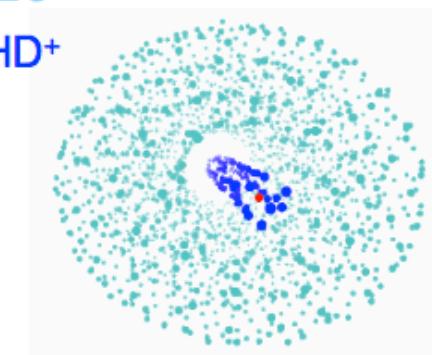


→



X
Y
Z

1800 Be^+
200 HD^+
1 \bar{H}^+

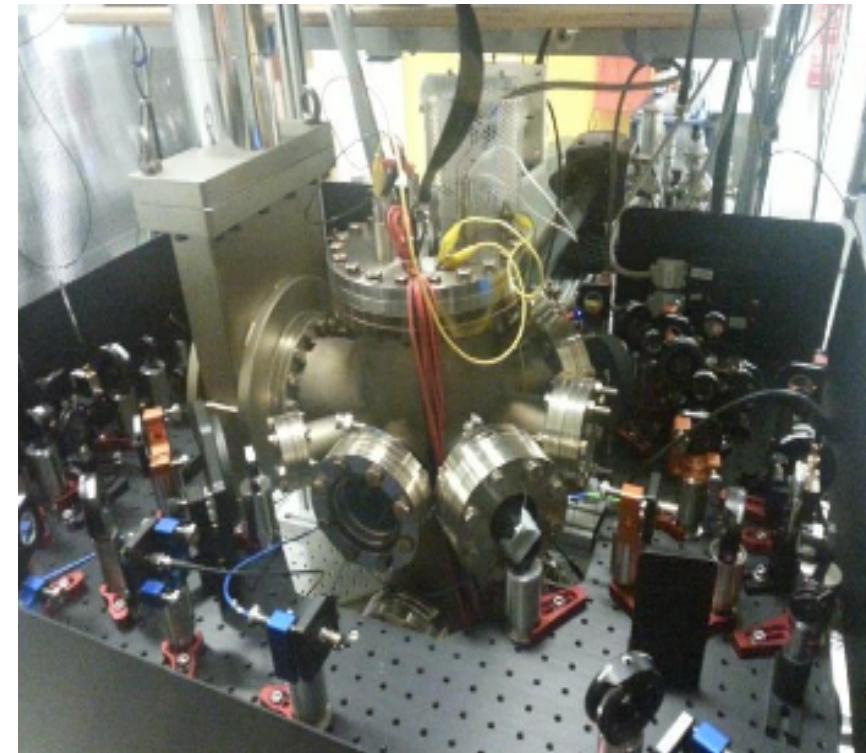
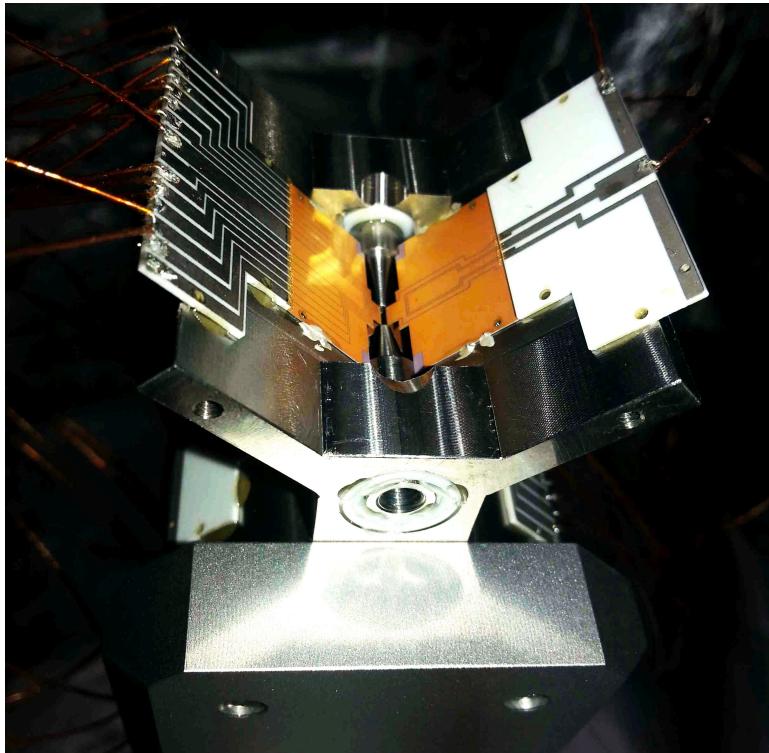


L. Hilico et al., (2014)
arXiv:1402.1695 [physics.atom-ph]

Precision trap

S. Wolf
F. Schmidt-Kaler

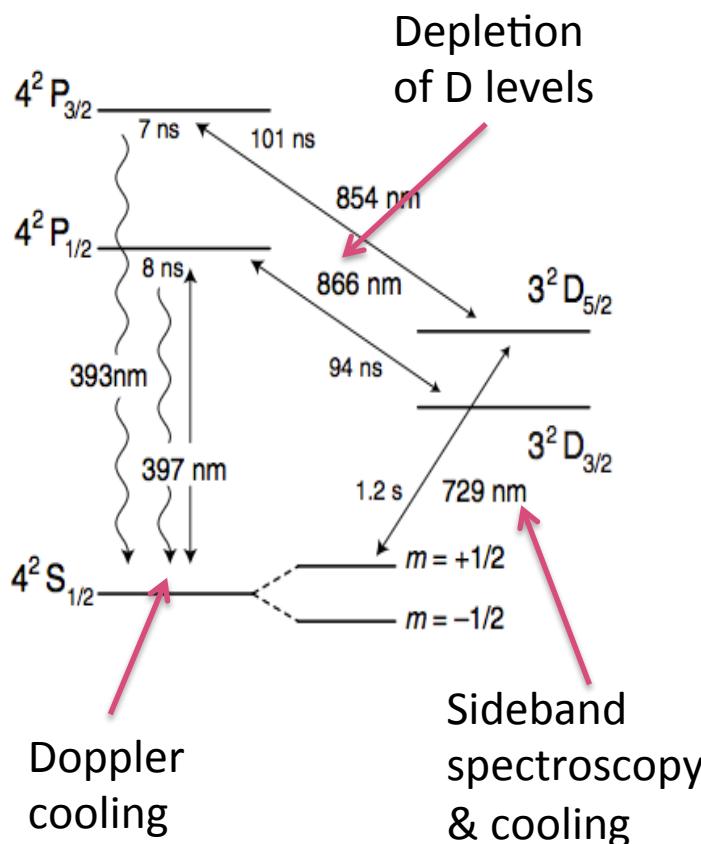
Precision trap prepared at Mainz
Tests with Ca^+/Be^+ , later Sr^+/Be^+



Precision trap

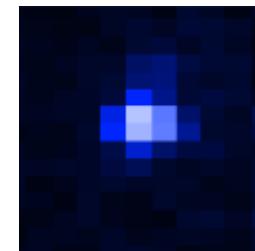
S. Wolf
F. Schmidt-Kaler

Precision trap tested at Mainz
tests with Ca^+/Be^+ , later Sr^+/Be^+

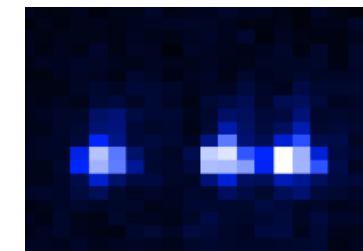


**2015: capture trap construction,
cooling of Ca^+/Be^+ ,
transport of ions between traps**
2016: cooling of H_2^+ with Be^+/HD^+ mix
2017: transport to CERN

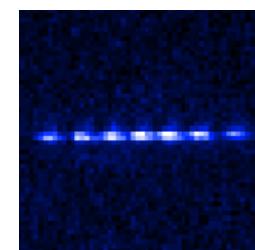
Ca⁺ crystals obtained



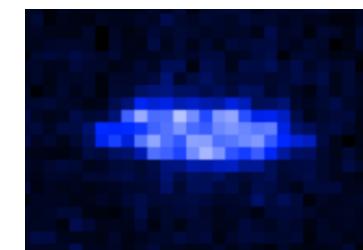
single



mixed



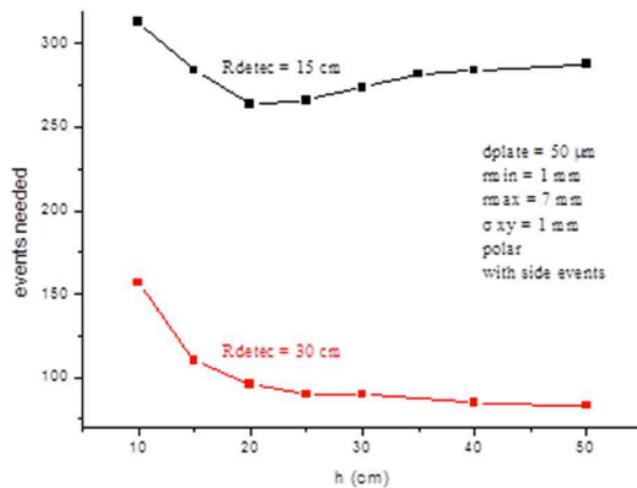
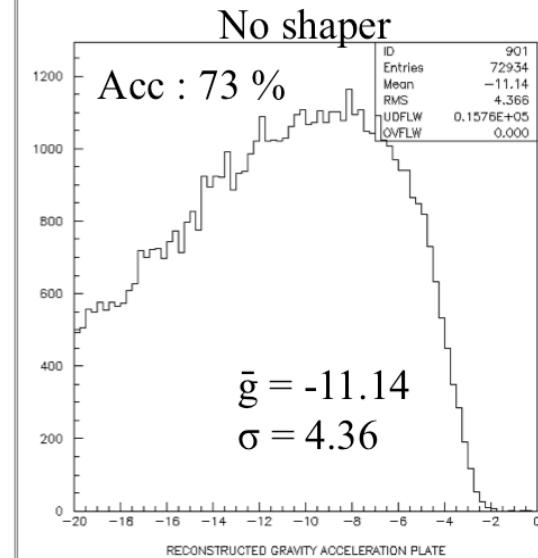
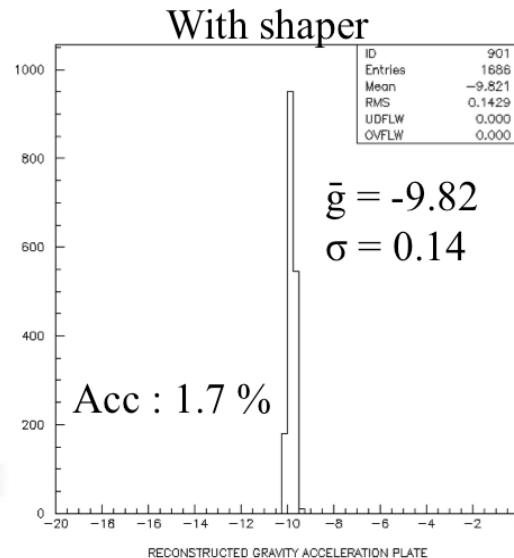
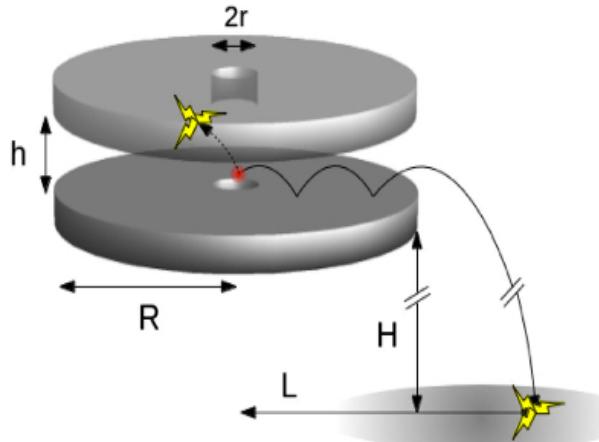
linear



zigzag

Velocity selector

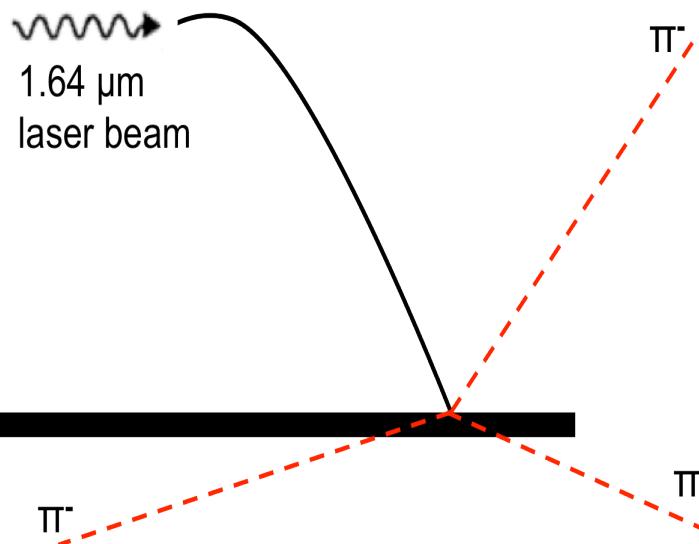
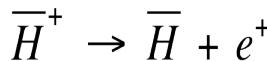
G. Dufour et al., Eur. Phys. J. C 74 (2014) 2731



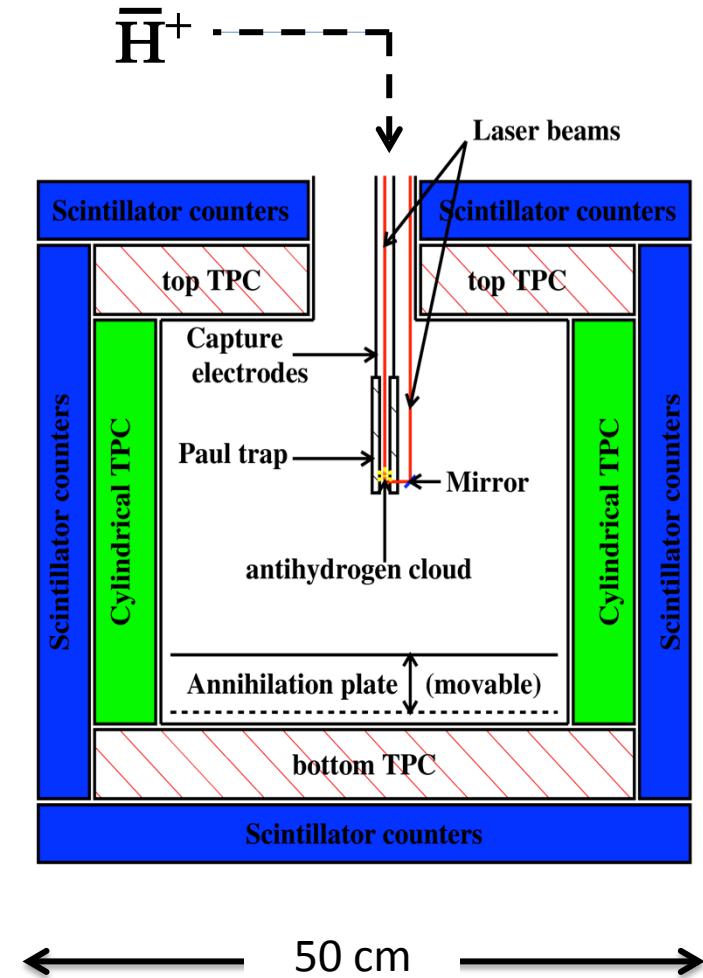
First simulations → optimise dimensions with experimental constraints
 $h = 50 \mu\text{m}$
 $H = 20 \text{ cm}$, $R_{\text{detector}} = 20 \text{ cm}$
Shaper $R_{\text{min}} = 1 \text{ mm}$, $R_{\text{max}} = 7 \text{ mm}$
→ need 150 produced $\overline{\text{H}}^+$ for $\Delta g/g = 1\%$
10 times less than in proposal

\bar{H} free fall detection

P. Debu IRFU
Saclay



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



MicroMegas detector

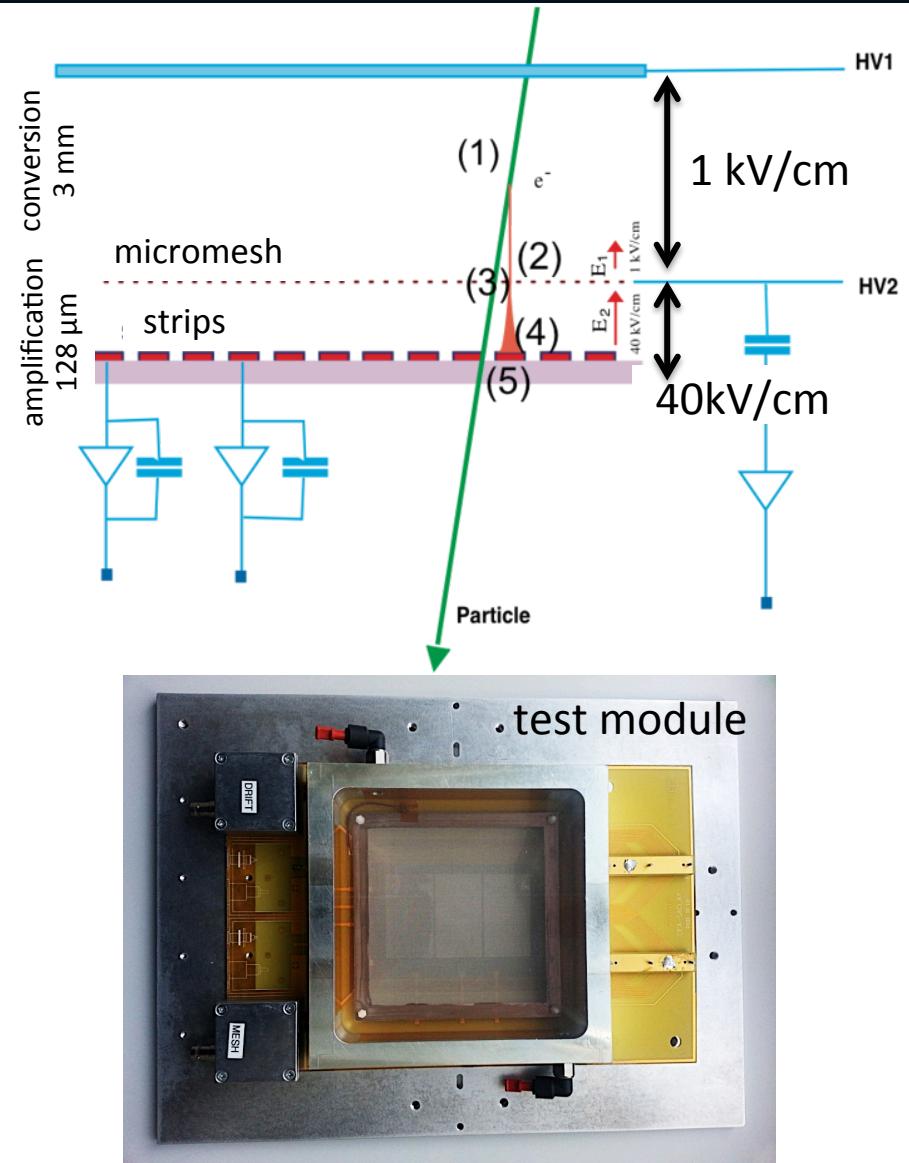
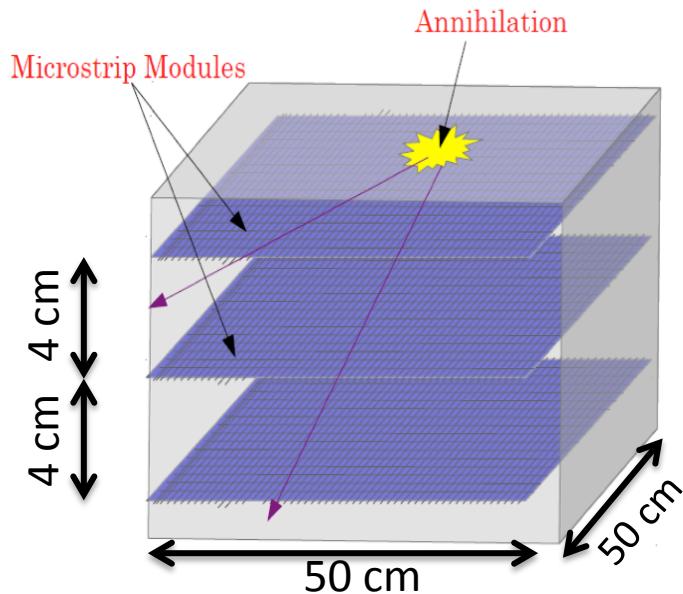
D. Banerjee, P. Crivelli
S. Aune, B. Vallage

Argon Isobutane (95% , 5%)

Pitch of strip \sim 400 microns

X and Y strips genetic multiplexing

2015: construction of 3 planes test bench tests with cosmic rays
2016: construction of full detector
2017: commissioning





D. Banerjee², F. Biraben⁷, D. Brook-Roberge⁵, M. Charlton¹¹, P. Cladé⁷, P. Comini⁵,
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P. Froelich¹⁴, P. Grandemange¹, S. Guellati⁷, R. Guérout⁷, J. M. Heinrich⁷, P.-A. Hervieux⁴,
L. Hilico⁷, A. Husson¹, P. Indelicato⁷, S. Jonsell¹⁵, J.-P. Karr⁷, K. Khabarova⁶,
N. Kolachevsky⁶, N. Kuroda¹², A. Lambrecht⁷, A.M.M. Leite⁵, L. Liszkay⁵, P. Lotrus⁵,
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T. Mortensen⁵, Y. Nagashima¹³, V. Nesvizhevsky³, F. Nez⁷, P. Pérez⁵, C. Regenfus²,
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F. Schmidt-Kaler⁸, N. Sillitoe⁷, M. Staszczak⁹, C. I. Szabo-Foster⁷, H. Torii¹², B. Vallage⁵,
M. Valdes⁴, D.P. van der Werf¹¹, A. Voronin⁶, J. Walz⁸, S. Wolf⁸, S. Wronka⁹,
Y. Yamazaki¹⁰.



Irfu



Laboratoire Kastler Brossel
Physique quantique et applications



Swansea University
School of Physical Sciences



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Świerk



P.N. Lebedev Physical
Institute of the Russian
Academy of Science



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UPPSALA
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Stockholm University

Layout

O. Choisnet
F. Butin

