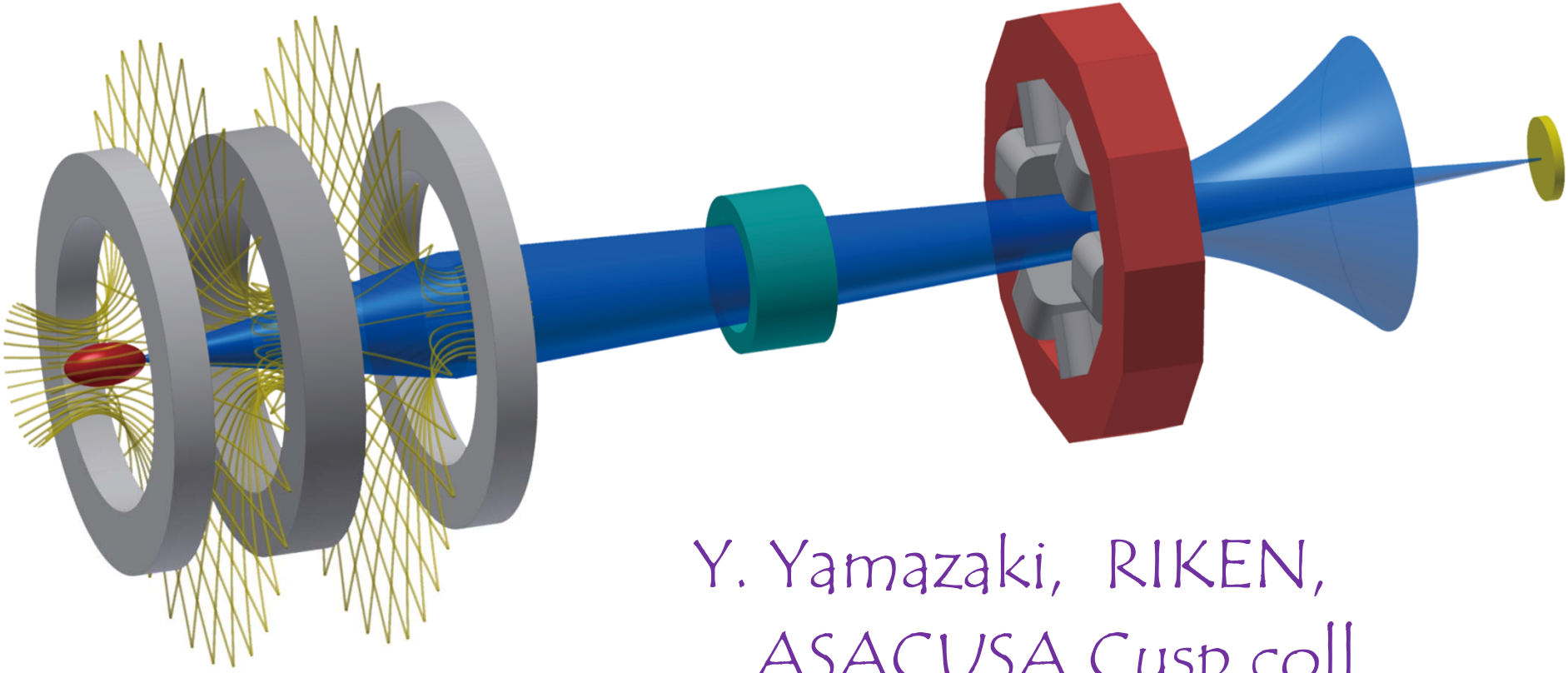
CEA, Saclay, May 2, 2016

Cold antihydrogen ($\overline{\mathrm{H}}$) Synthesis for Hyperfine spectroscopy and ASACUSA Micromegas Tracker (AMT)



Y. Yamazaki, RIKEN,
ASACUSA Cusp coll.

Motivation

☆Tests of CPT symmetry comparing $\bar{H}$ & H

(CPT: Charge conjugation, Parity, Time reversal)

* CPT symmetry is guaranteed by the Standard model, which assumes flat space-time, local interaction, Lorentz invariance, and unitarity (e.g., gravitational interaction, non-local interaction may violate CPT.)

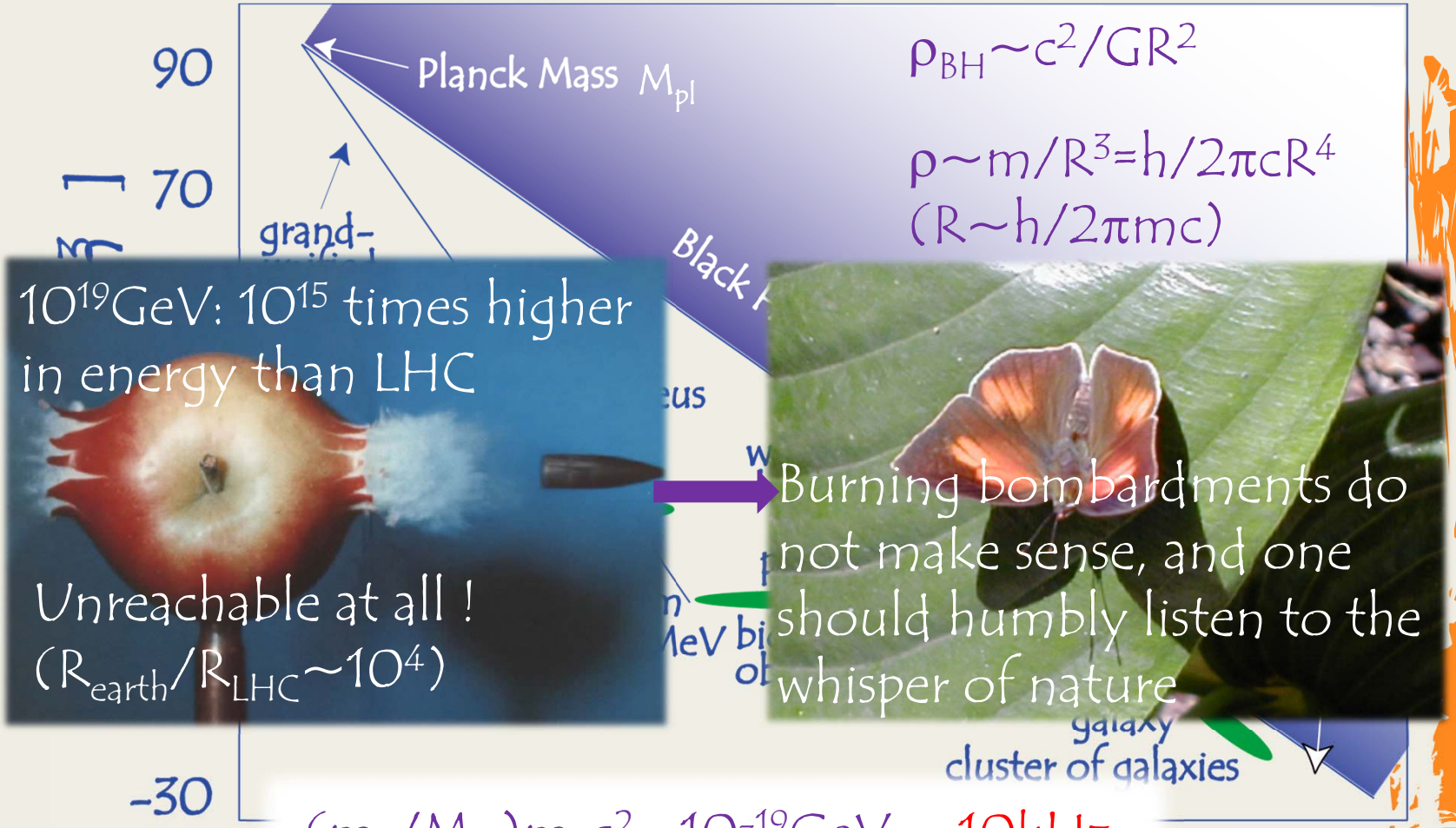
* Violation of P, CP, T

* Finite neutrino mass

* Dark matter, dark energy

☆ CPT symmetry ←→ m, |q|, |μ|, τ, spectroscopic properties are **exactly** the same between matter and antimatter

CPT symmetry



10^{19}GeV: 10^{15} times higher in energy than LHC

Unreachable at all !
($R_{earth}/R_{LHC} \sim 10^4$)

Burning bombardments do not make sense, and one should humbly listen to the whisper of nature

$(m_p/M_{pl})m_pc^2 \sim 10^{-19}$GeV ~10kHz

Motivation

K^0 & $\overline{K}^0$: known to be most precise CPT test

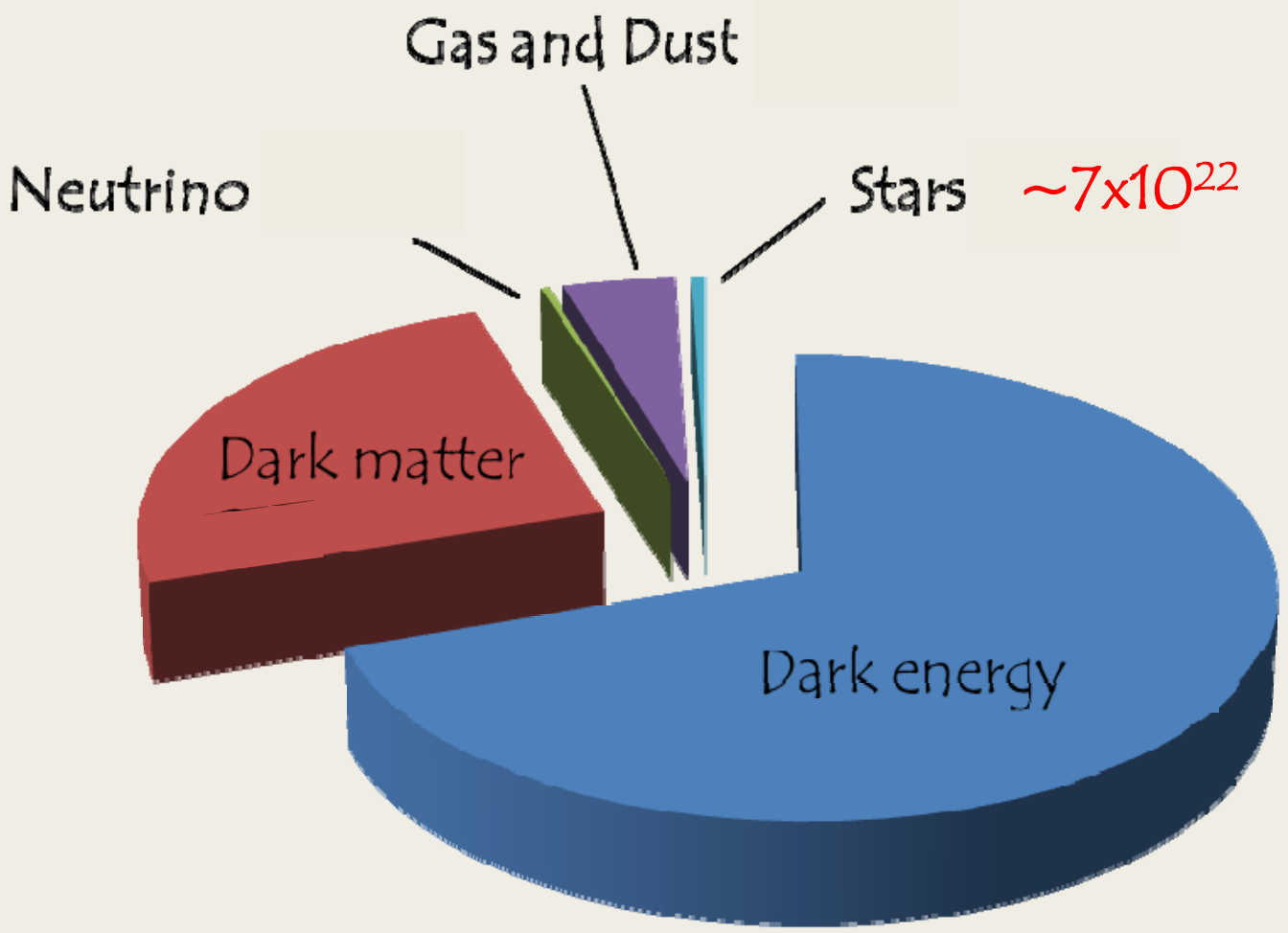
$|m(K^0)-m(\overline{K}^0)|/m(K) < 6 \times 10^{-19}$

Or $|m(K^0)-m(\overline{K}^0)| < 4 \times \underline{10^{-19}\ \text{GeV}}$

Cf. CP violation: $Im(m_{12}) \sim 1.1 \times 10^{-17}$ GeV

*M. Kobayashi and A.I. Sanda, PRL 69 (1992) 3139

Motivation



Our understanding is limited in 5% of the total energy of the universe.... ← a frog in a well

Motivation

Standard Model Extension: Artificial inclusion of CPT and Lorenz violating interactions, and evaluate sensitive physical quantities (Kostelecky et al.)

$$(i\gamma^{\mu}D_{\mu} - m - a_{\mu}\gamma^{\mu} - b_{\mu}\gamma_5\gamma^{\mu} - \frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^{\mu}D^{\nu} + id_{\mu\nu}\gamma_5\gamma^{\mu}D^{\nu})\psi = 0$$

where $iD_{\mu} = i\partial_{\mu} - qA_{\mu}$ and $\hbar = c = 1$

→

☆Hyperfine transitions have the 1st order sensitivity to the CPTV term

☆ Compare quantities in energy scale

R. Bluhm et al., PRL82(1999)2254

Motivation

	$\Delta(q/m)/(q/m)$	$\lvert m_m-m_a\rvert/m$	$\lvert q_m+q_a\rvert/\lvert q\rvert$	$\lvert q_m-q_a\rvert/\lvert q\rvert$
e.g., 1S-2S transition:		$h\Delta\nu/m_e c^2 \sim$		4.2×10^{-15}
e^- vs e^+		$<8\times10^{-9}$	$<4\times10^{-8}$	4.6×10^{-23} $(-0.5\pm2.1)\times10^{-12}$
Hyperfine transition:		$h\Delta\nu/m_H c^2 \sim$		6.3×10^{-13}
p vs $\bar{p}$	$(1\pm69)\times10^{-12}$	$<7\times10^{-10}$	$<7\times10^{-10}$	$<5\times10^{-6}$ 4.0×10^{-27}

$g_p/2 = 2.792847356(23)$ (maser)

$g_p/2 = 2.792847350(7)(6)$ (trap) A. Mooser, et al., Nature 509, 596 (2014)

H	experiments (Hz)	$\Delta\nu_{exp}/\nu$	$\lvert\nu_{th}-\nu_{exp}\rvert/\nu$
ν_{1S-2S}	2,466,061,413,187,035 (10)	4.2×10^{-15}	1×10^{-11}
ν_{HF}	1,420,405,751.7667 (9)	6.3×10^{-13}	$(3.5\pm0.9)\times10^{-6}$

Red letter: theoretical limit for H

Unknown physics if at all should be seen below this theoretical limit, i.e., should at least be 10^4 Hz or better, which is again 10^{-19} GeV

$\bar{H}$ Synthesis and manipulation

(1) $\bar{p} + e^+ \rightarrow \bar{H} + h\nu$ $\quad \Gamma = 3 \cdot 10^{-11} (4.2/T)^{1/2} \rho_e \rho_{\bar{p}} \ s^{-1}$

(2) $\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$ $\quad \Gamma = 6 \cdot 10^{-13} (4.2/T)^{9/2} \rho_e^2 \rho_{\bar{p}} \ s^{-1}$

(ATRAP, ALPHA, ASACUSA)

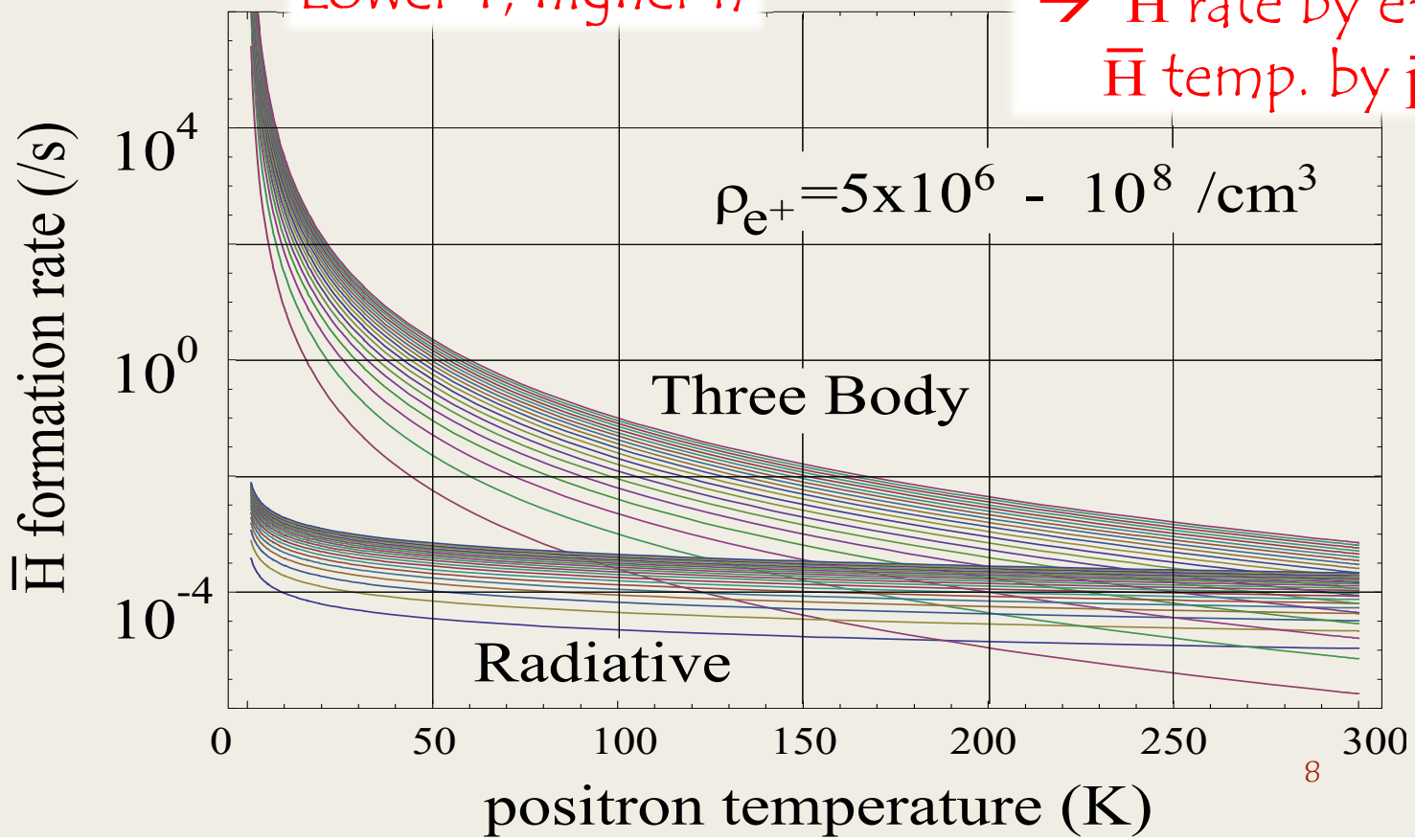
(3) $\bar{p} + (e^+e^-) \rightarrow \bar{H} + e^-$ (ATRAP, AEgIS, Gbar($\bar{H}^+$))

e+ temp.

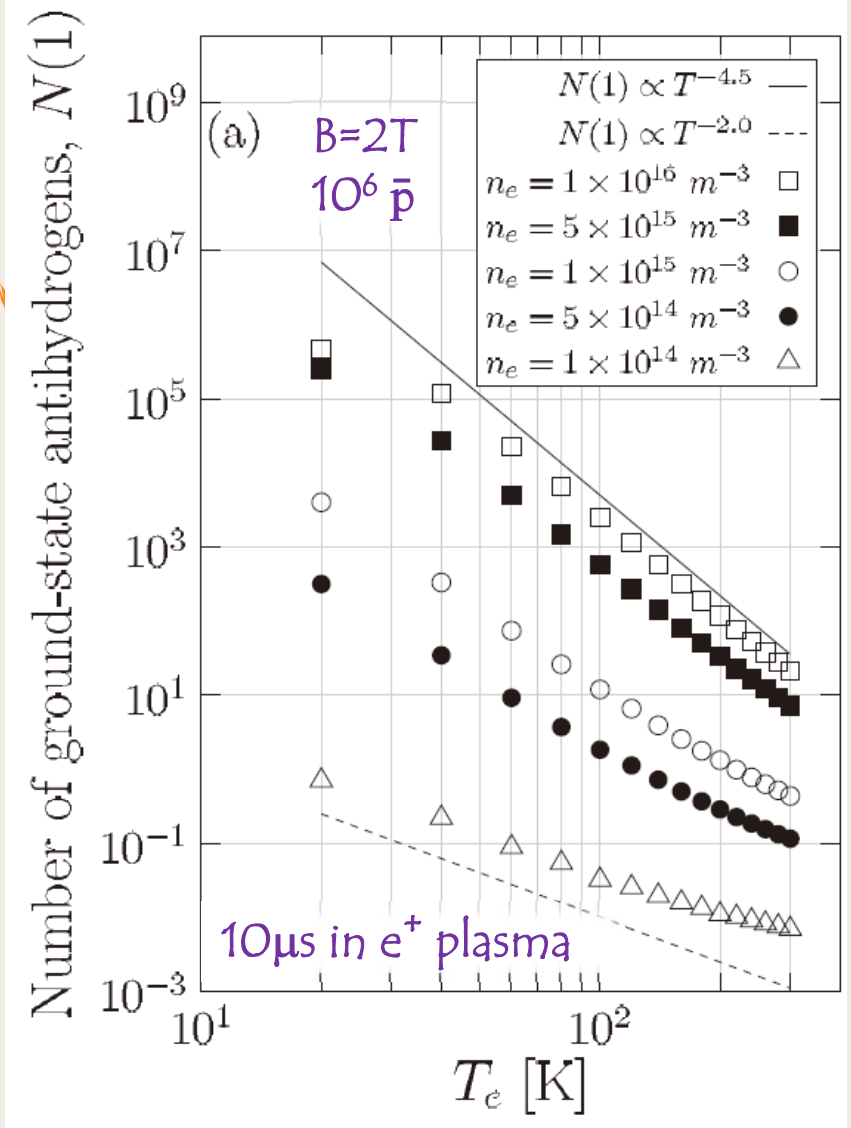
Lower T, higher n

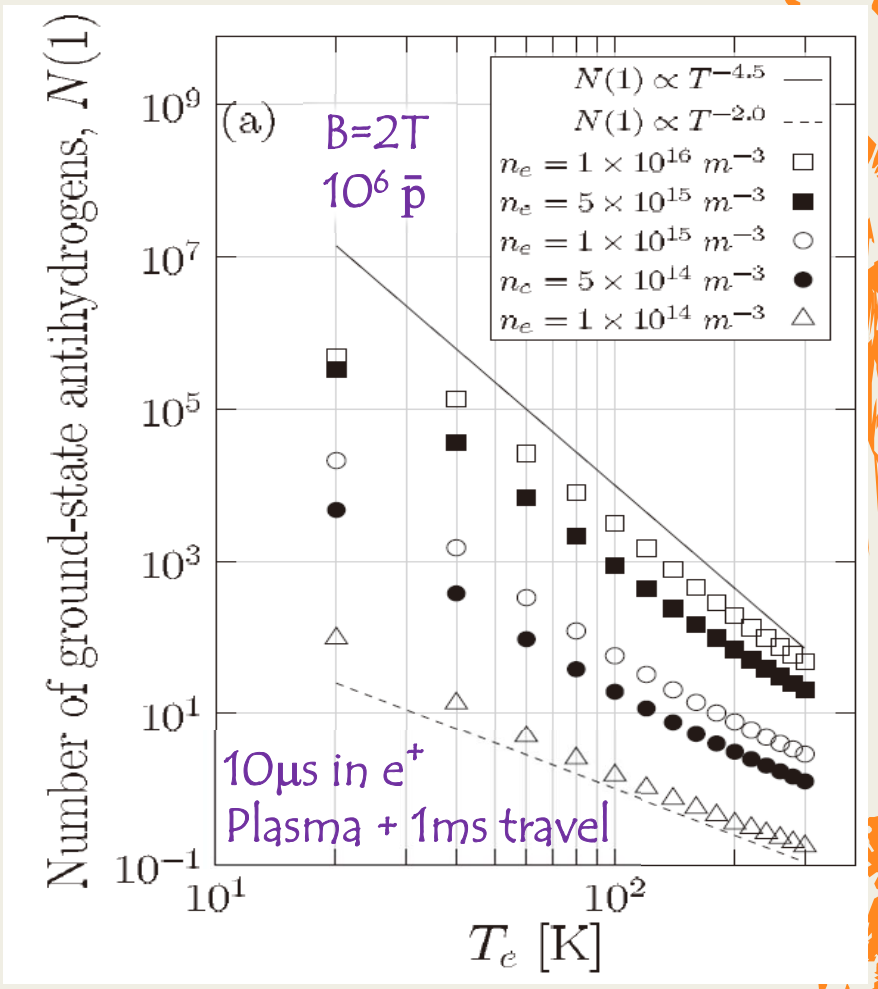
→ $\bar{H}$ rate by e+ temp.

$\bar{H}$ temp. by $\bar{p}$ temp.



$\bar{H}$ Synthesis and manipulation

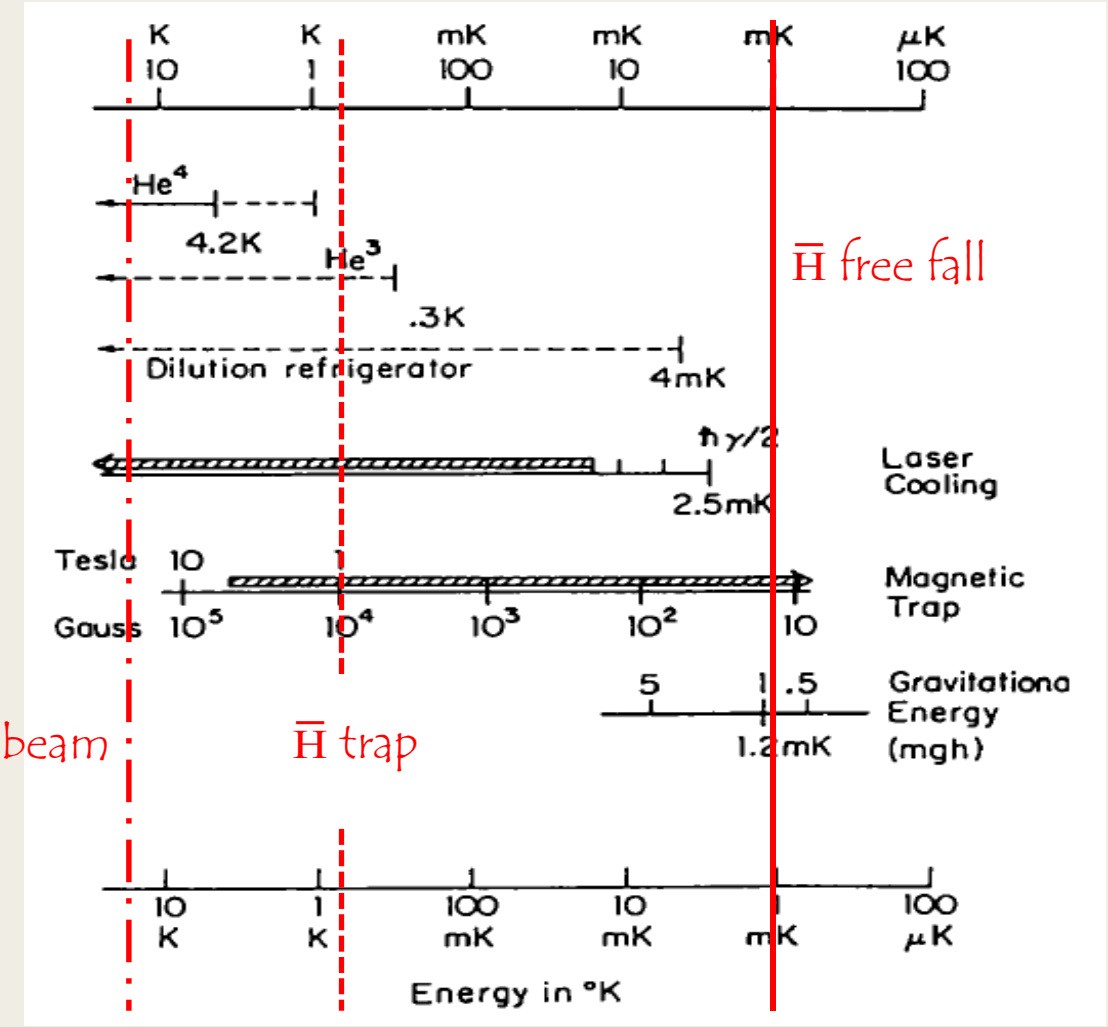




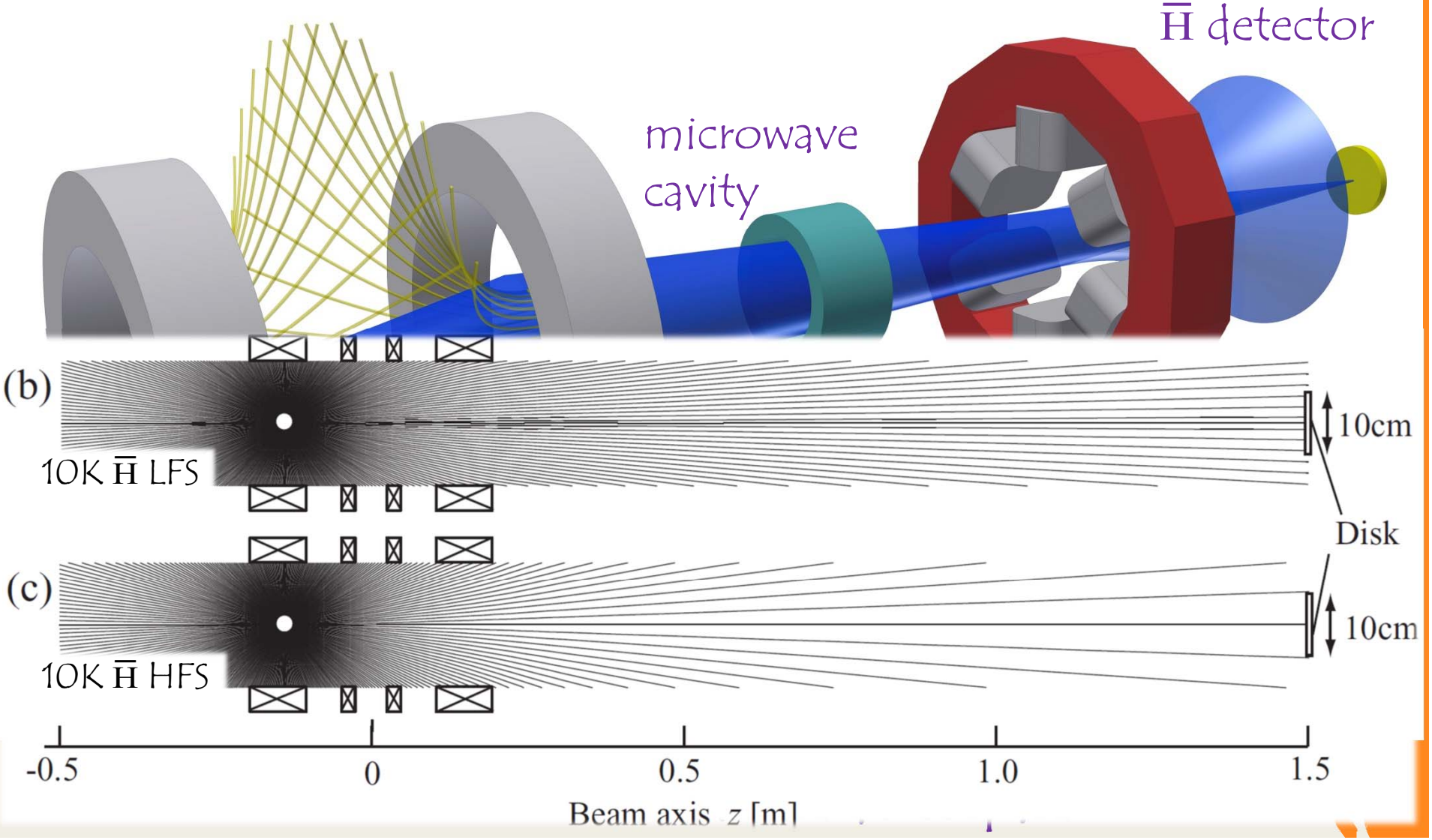
e+: higher n_e, lower T

B. Radics, D. J. Murtagh, Y. Yamazaki, F. Robicheaux, Phys. Rev. A 90, 032704 (2014)

$\bar{H}$ Synthesis and manipulation

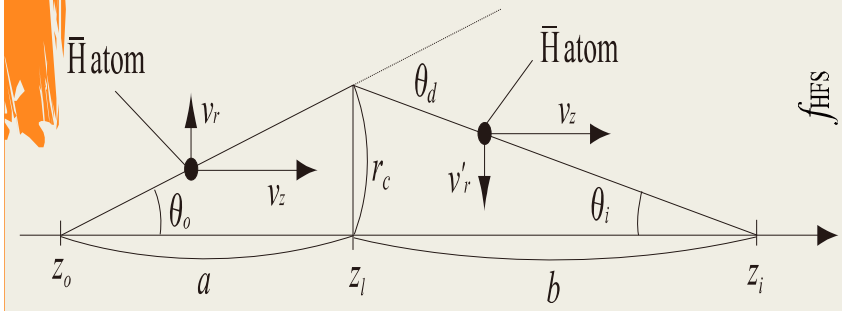


Cusp scheme for polarized $\bar{H}$ beam

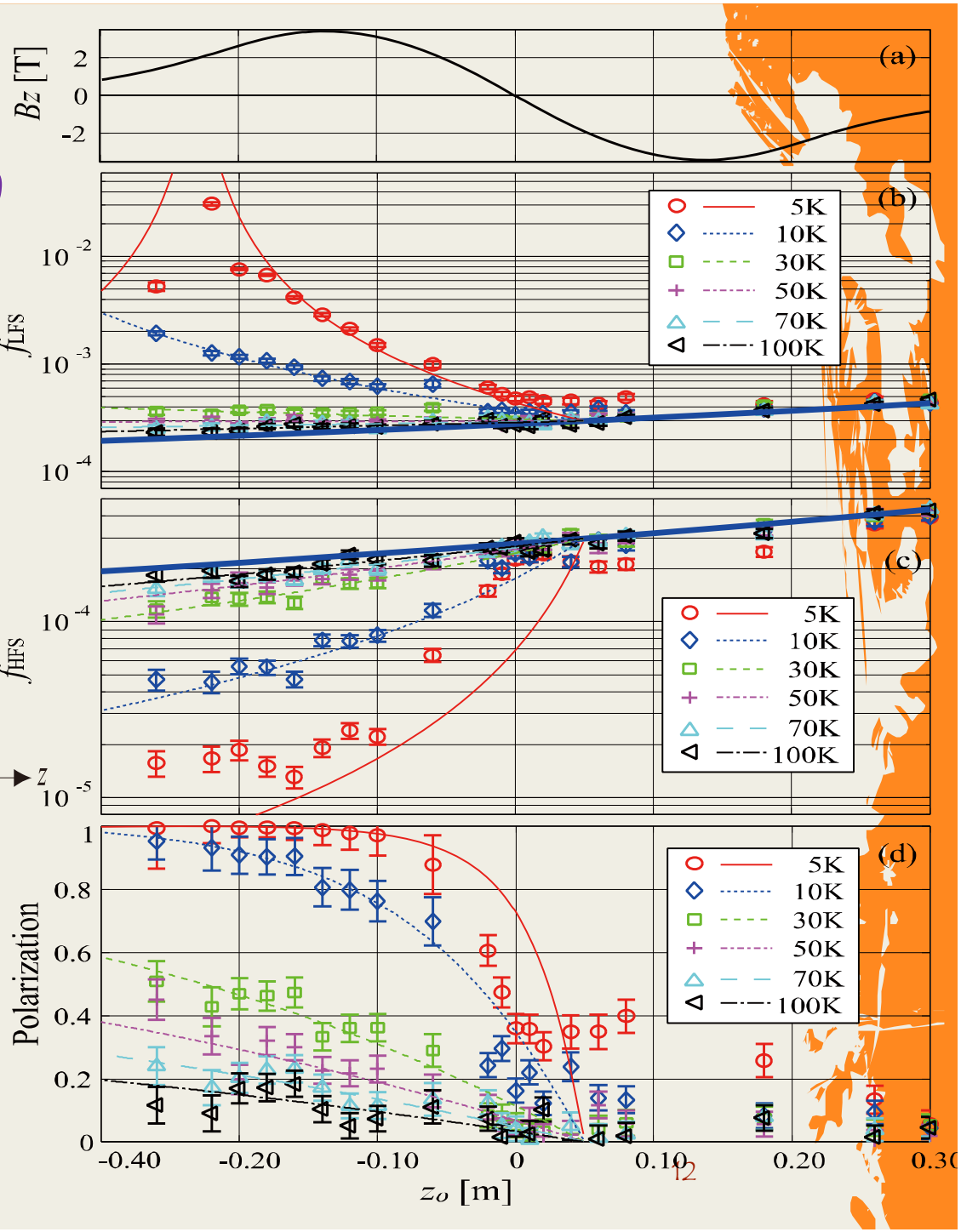


Cusp scheme for polarized $\bar{H}$ beam

$1/f = 1/a + 1/b$?



Nagata et al., NJP16(2014)083026



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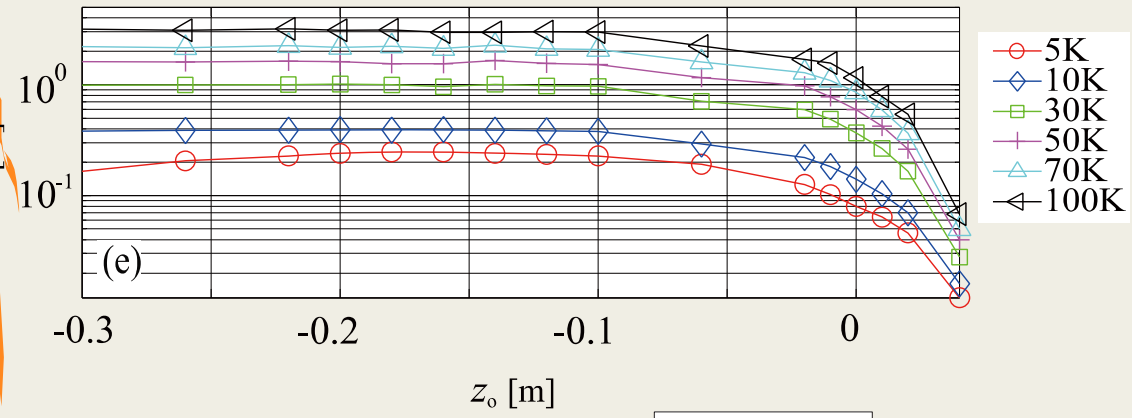
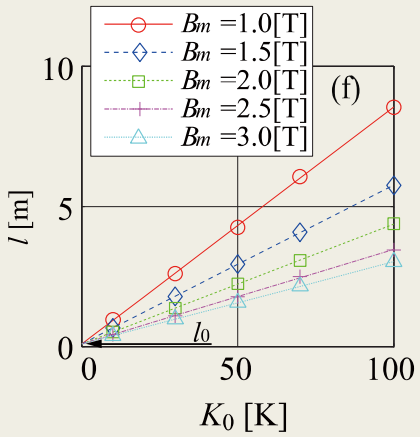
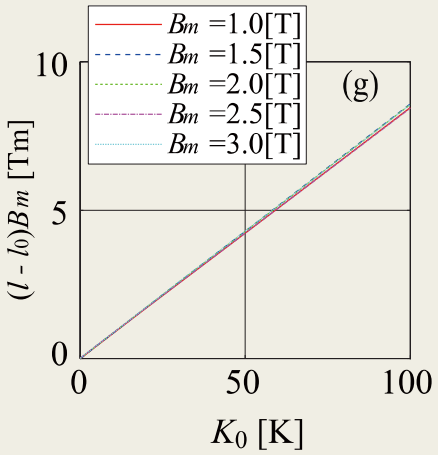
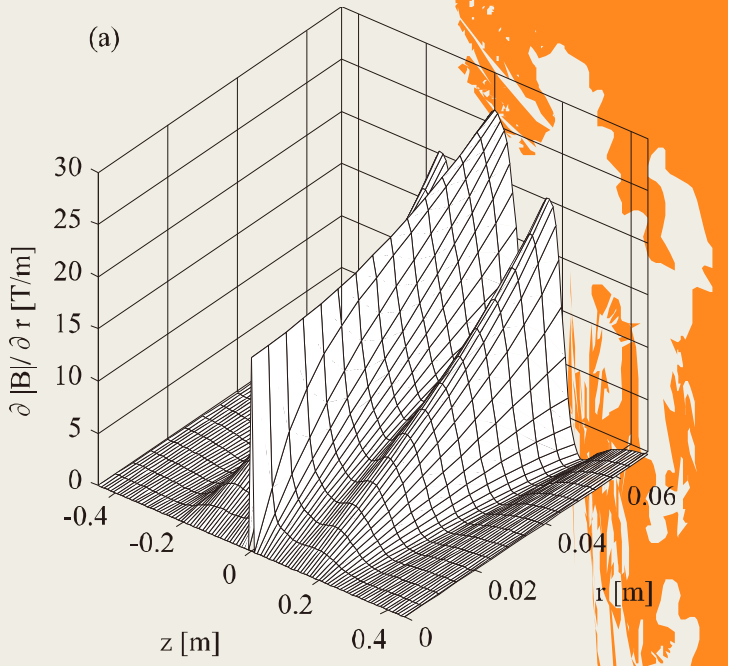
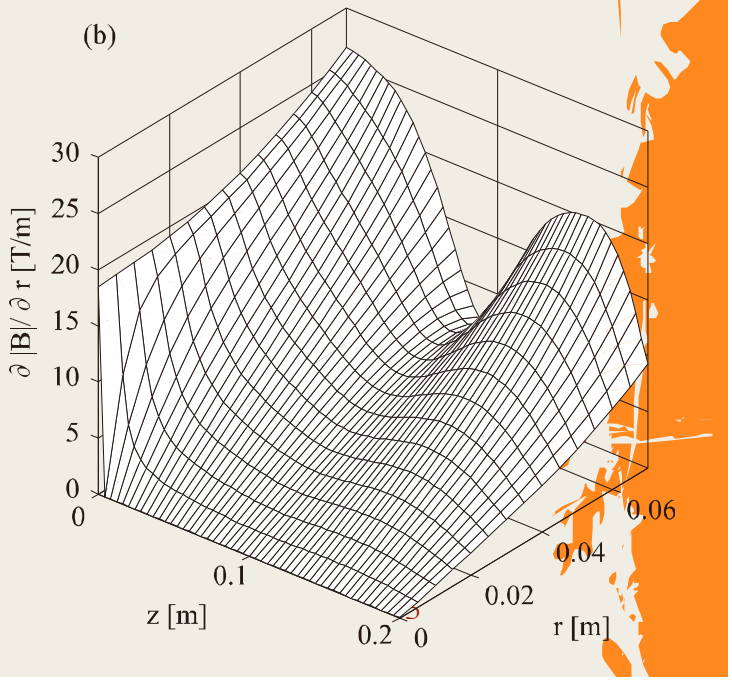






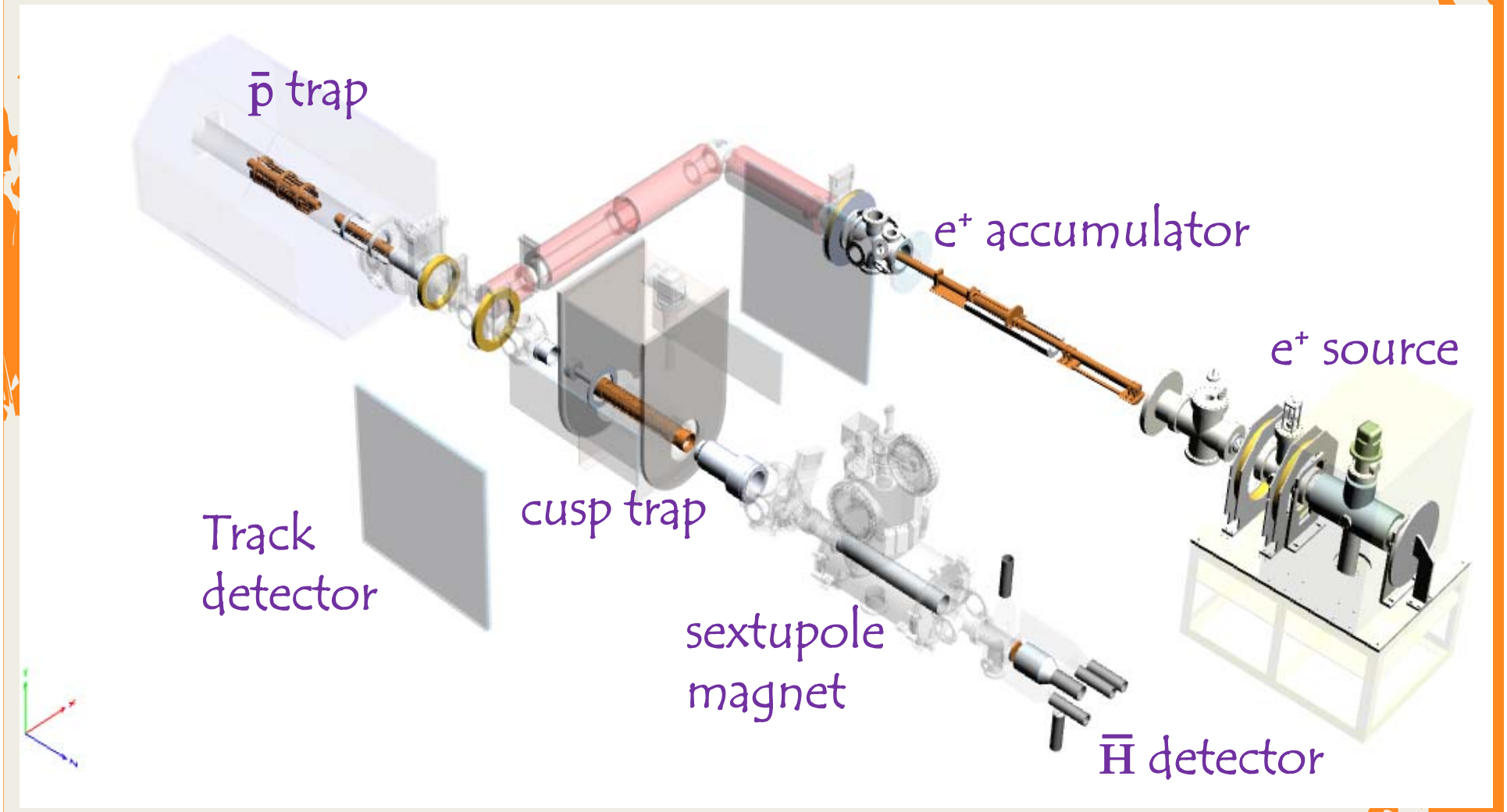




Yes, $1/f = 1/a + 1/b$!

f_{LFS}[m] =0.085 (K_0[K]+ 1.1B_m[T]) / B_m[T]

Cusp scheme for polarized $\bar{H}$ beam



N. Kuroda et al., Nature Communication 4089 (2014)

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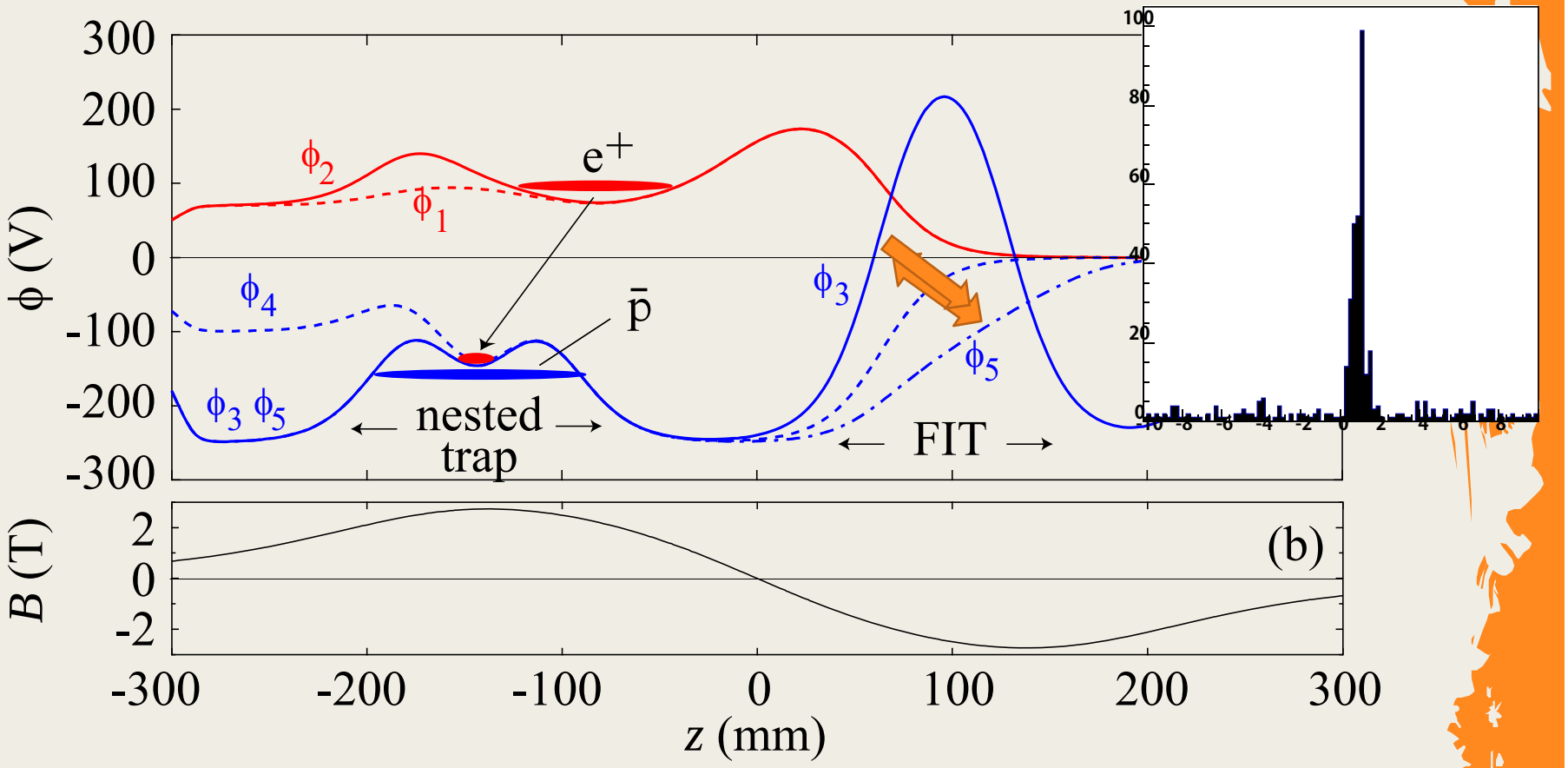
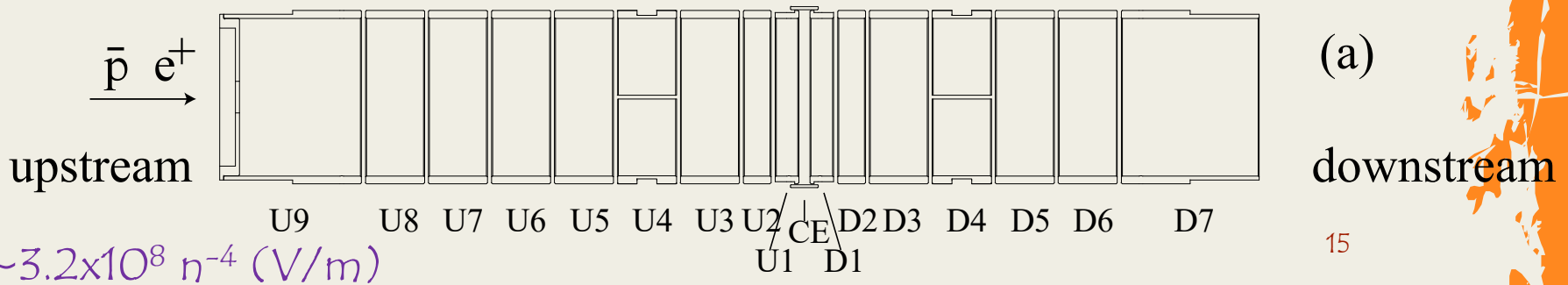
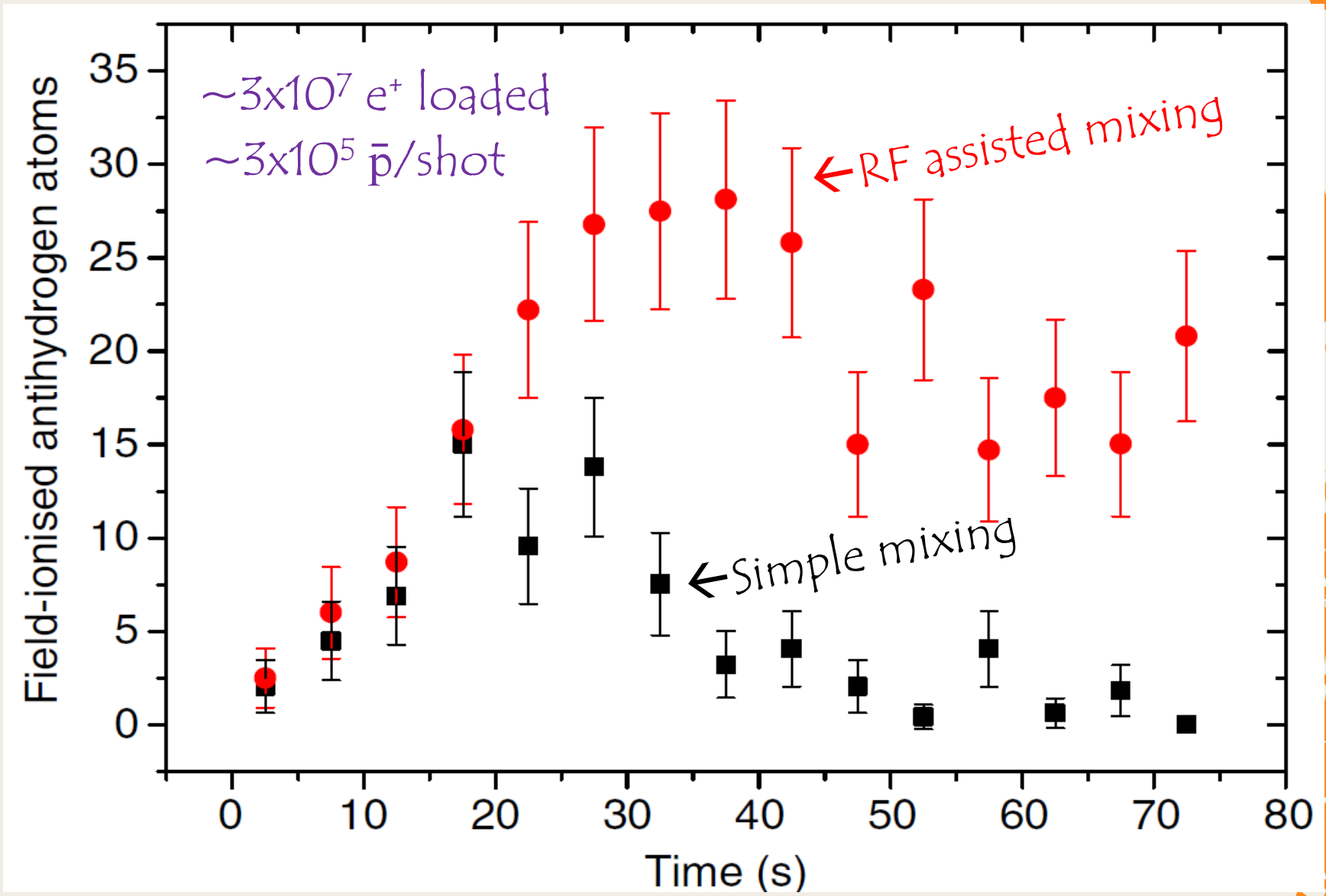




F~3.2x10^{8} n^{-4} (V/m)

Cusp scheme for polarized $\bar{H}$ beam



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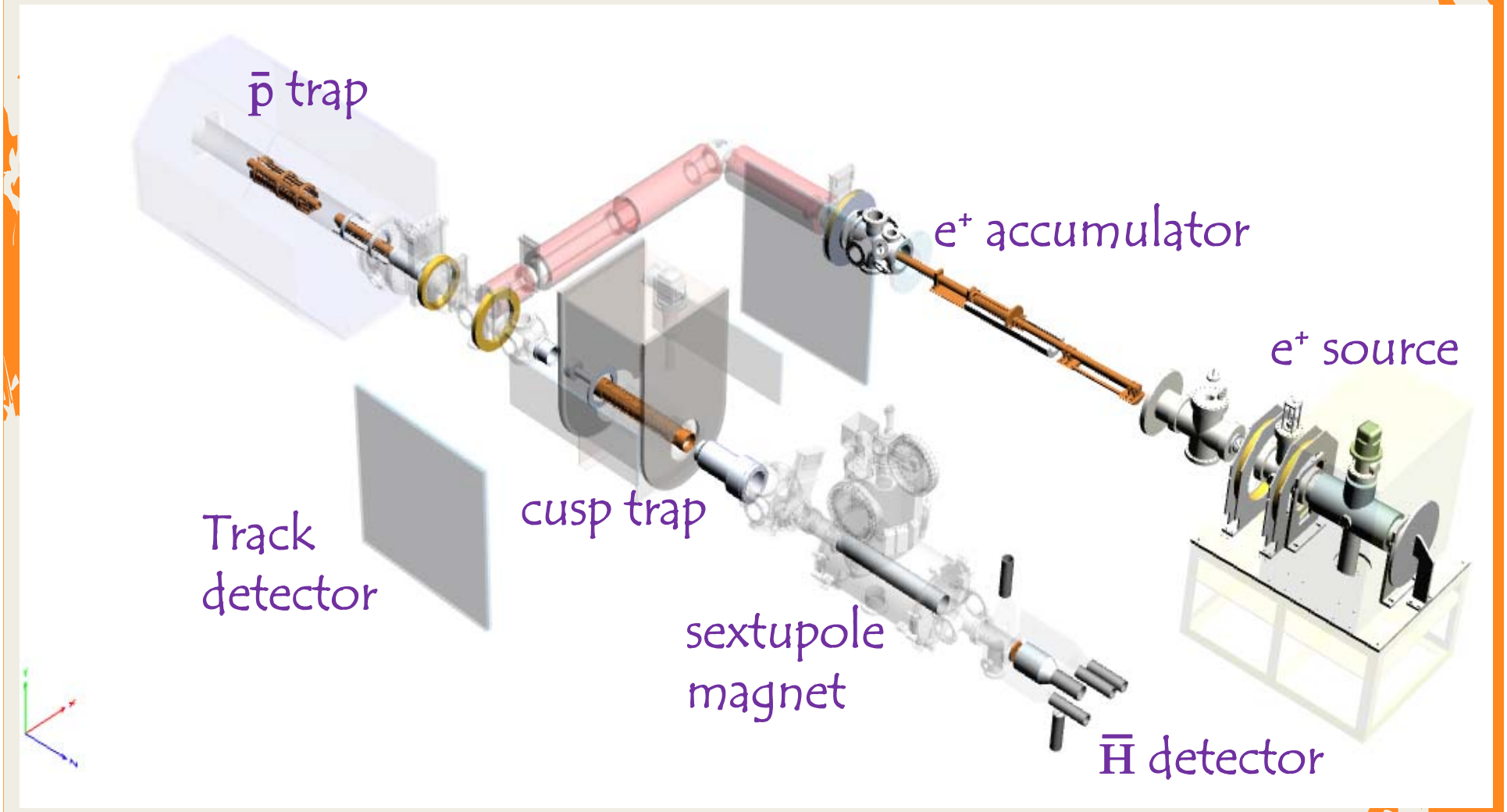

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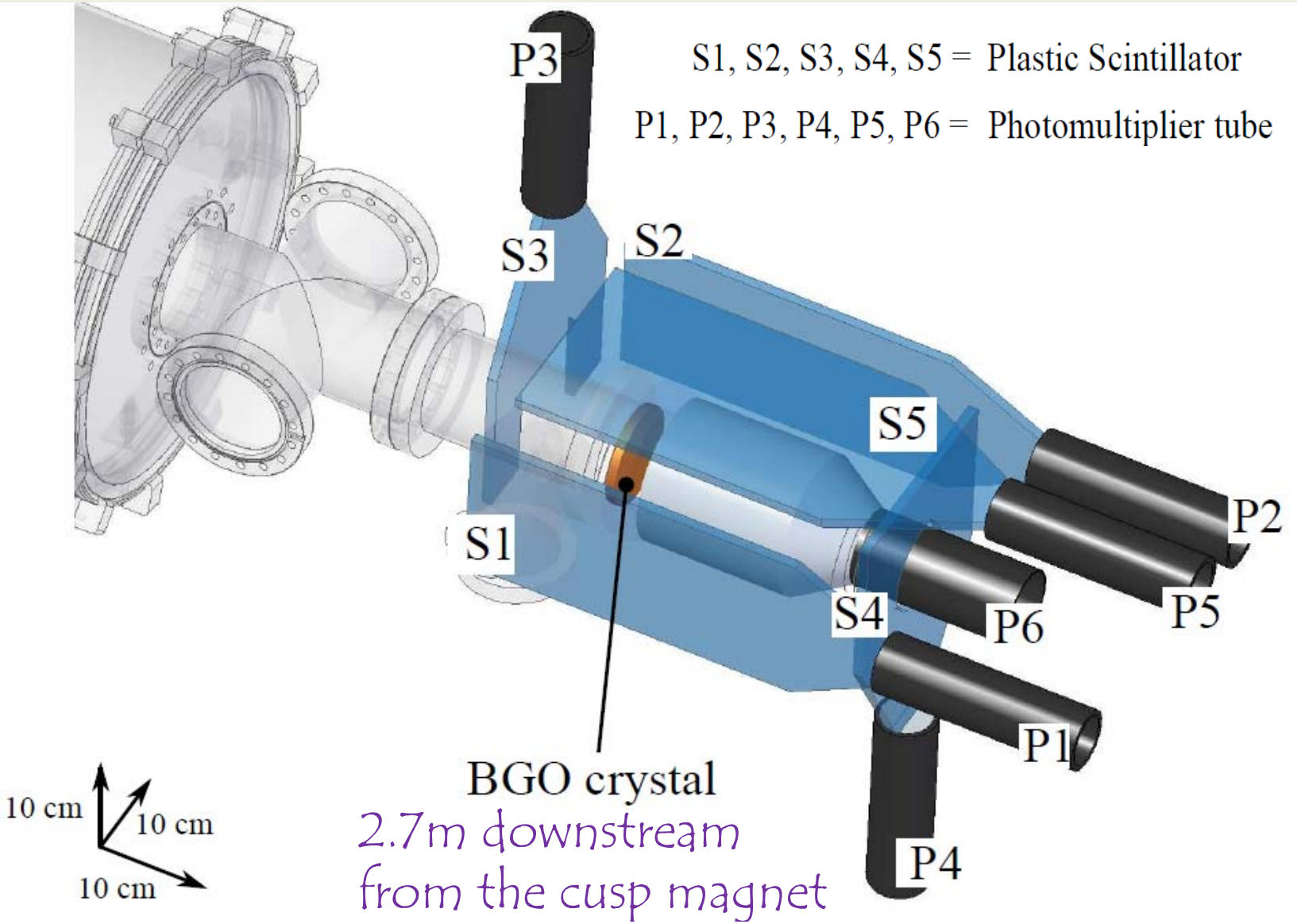
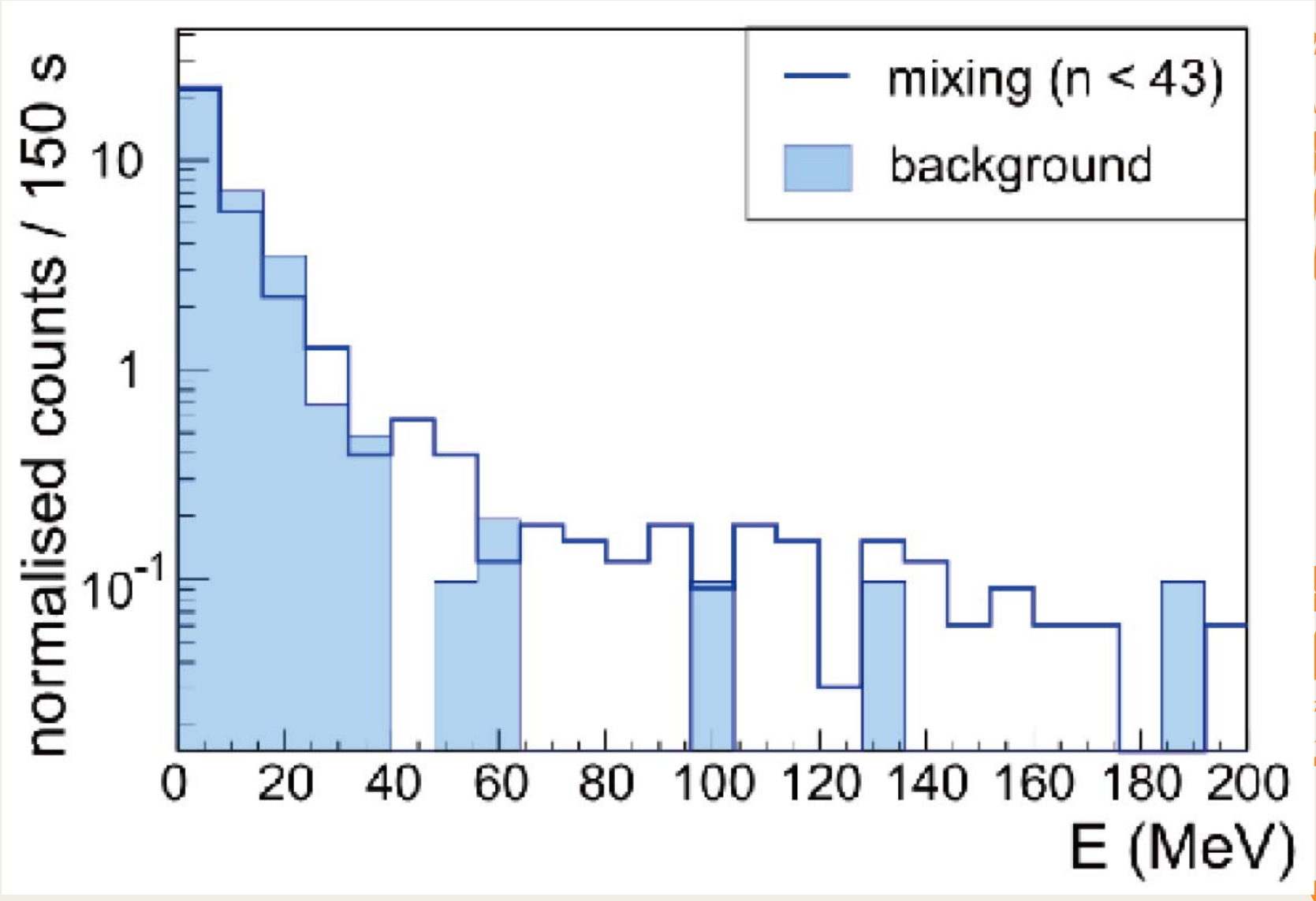


2.7m downstream
from the cusp magnet

Cusp scheme for polarized $\bar{H}$ beam



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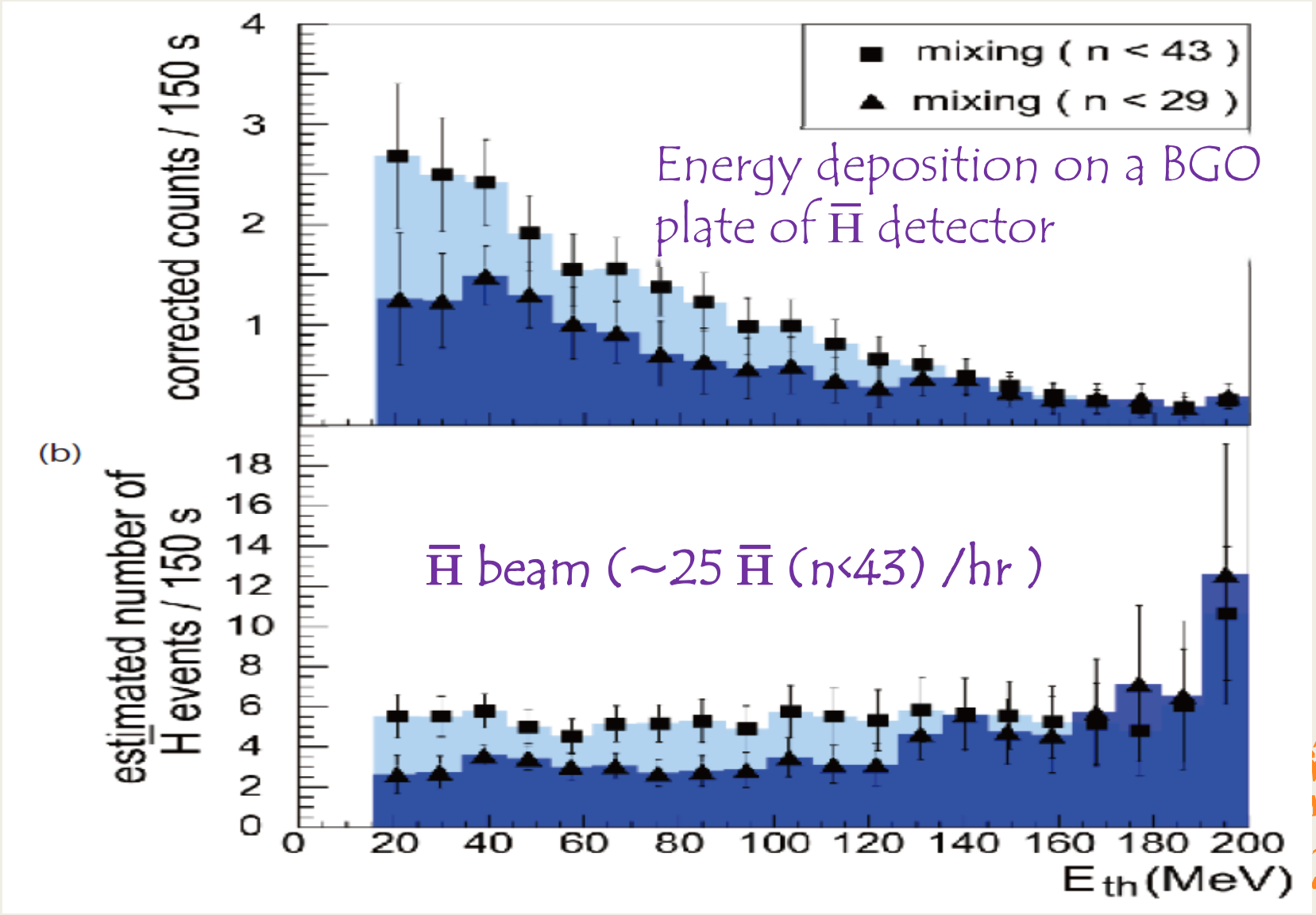
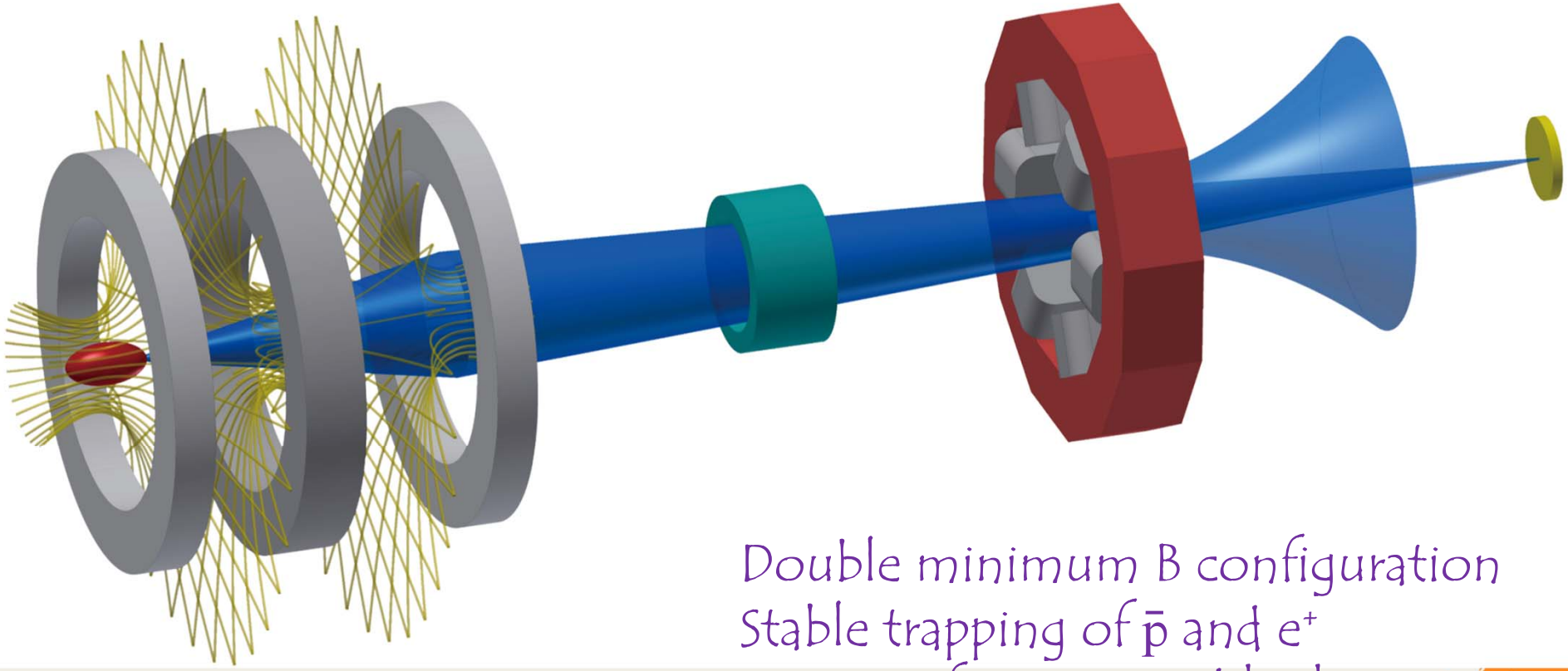


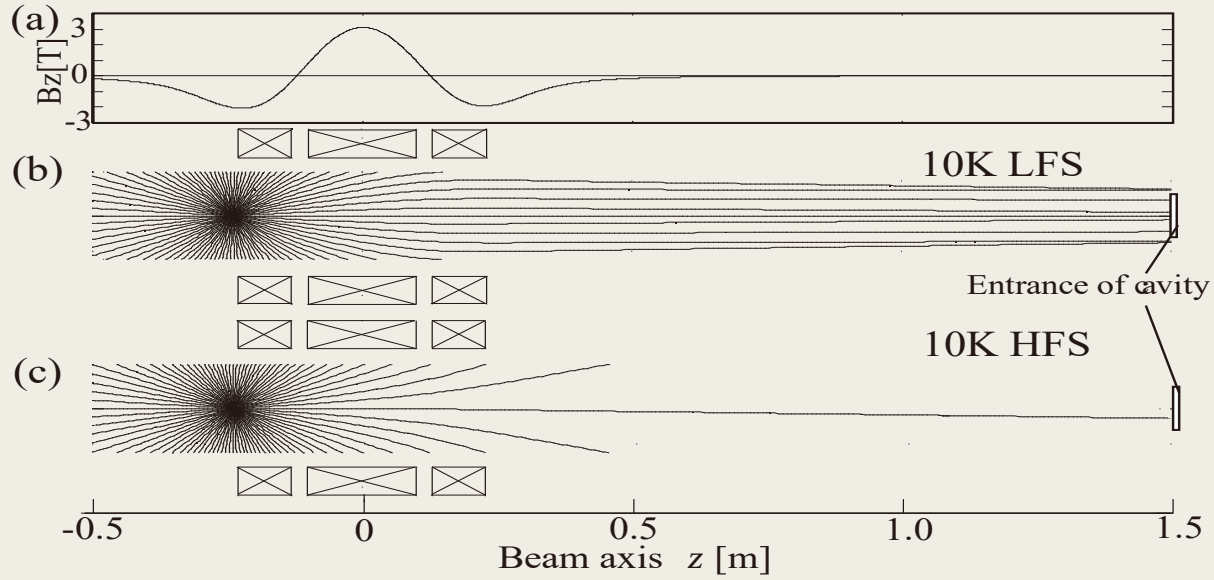
N. Kuroda et al., Nature Communication 4089 (2014)

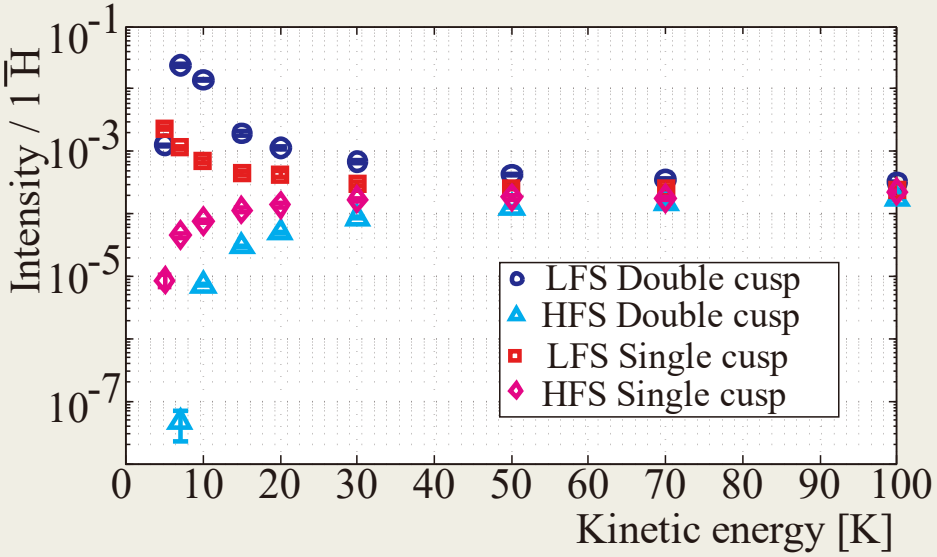
Double cusp magnet for polarized $\bar{H}$ beam

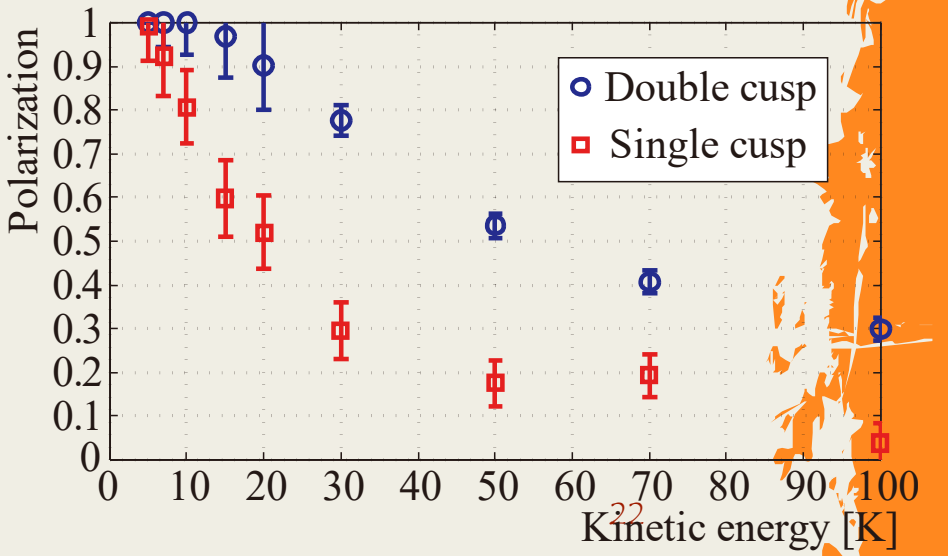


Double minimum B configuration
Stable trapping of $\bar{p}$ and e^+
Stronger focusing and higher spin-polarized $\bar{H}$ beam
$\bar{H}$ in B field free space

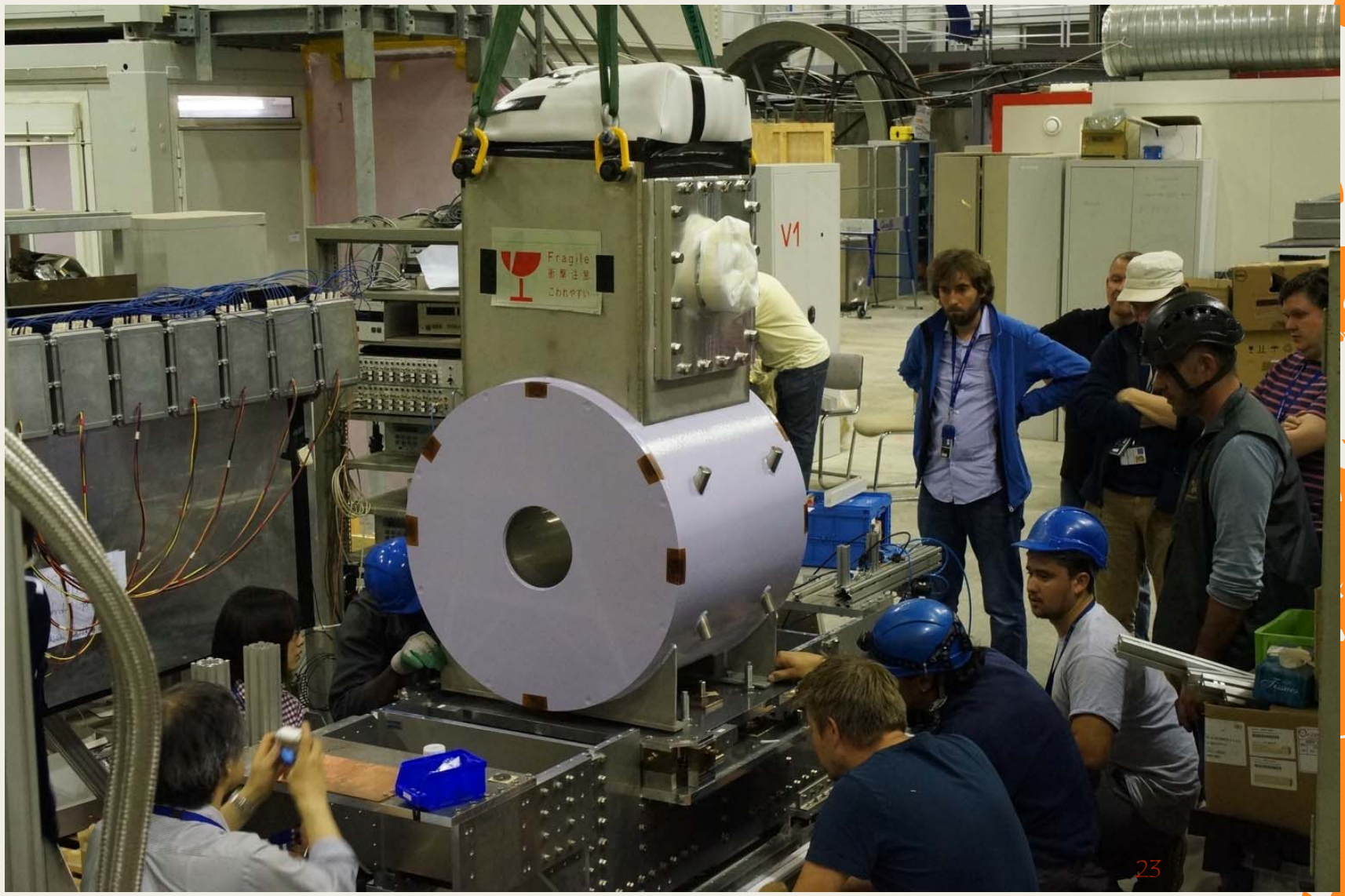
Double cusp magnet for polarized $\bar{H}$ beam







Double cusp magnet for polarized $\bar{H}$ beam



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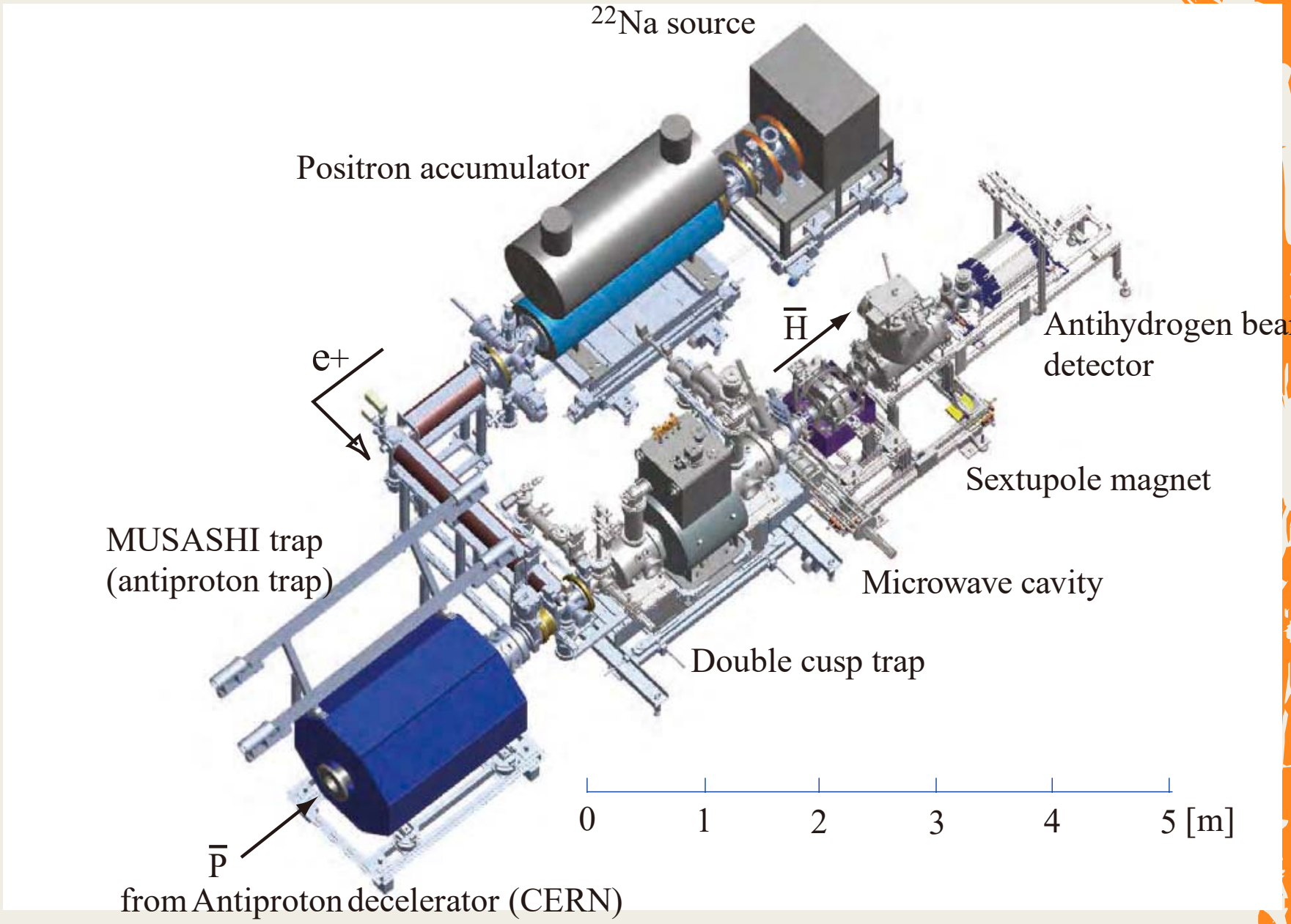
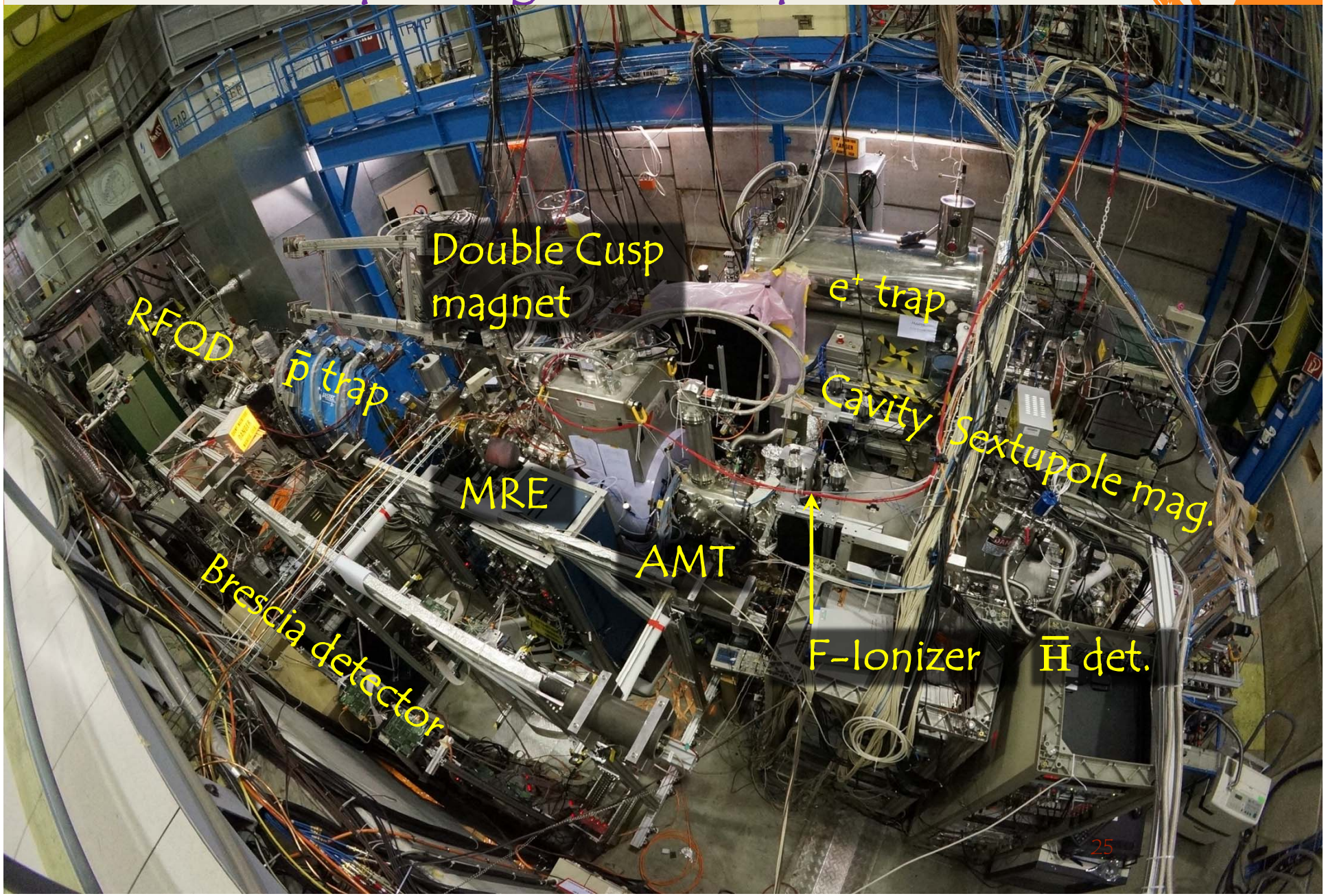
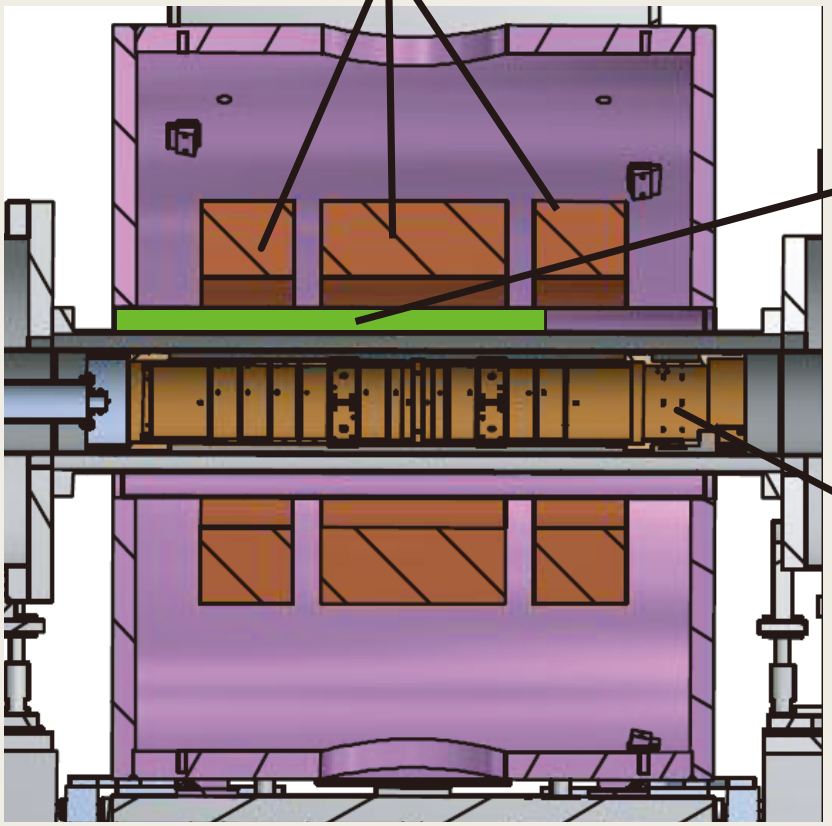


Double cusp magnet for polarized $\bar{H}$ beam



Double cusp magnet for polarized $\bar{H}$ beam

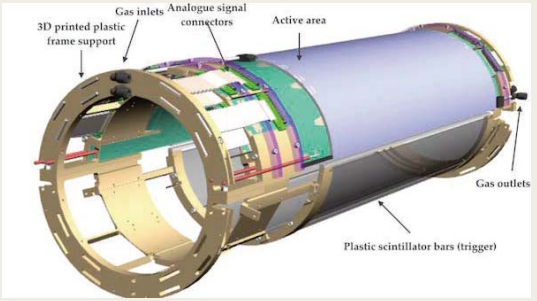
Double cusp magnet



$\bar{p}$

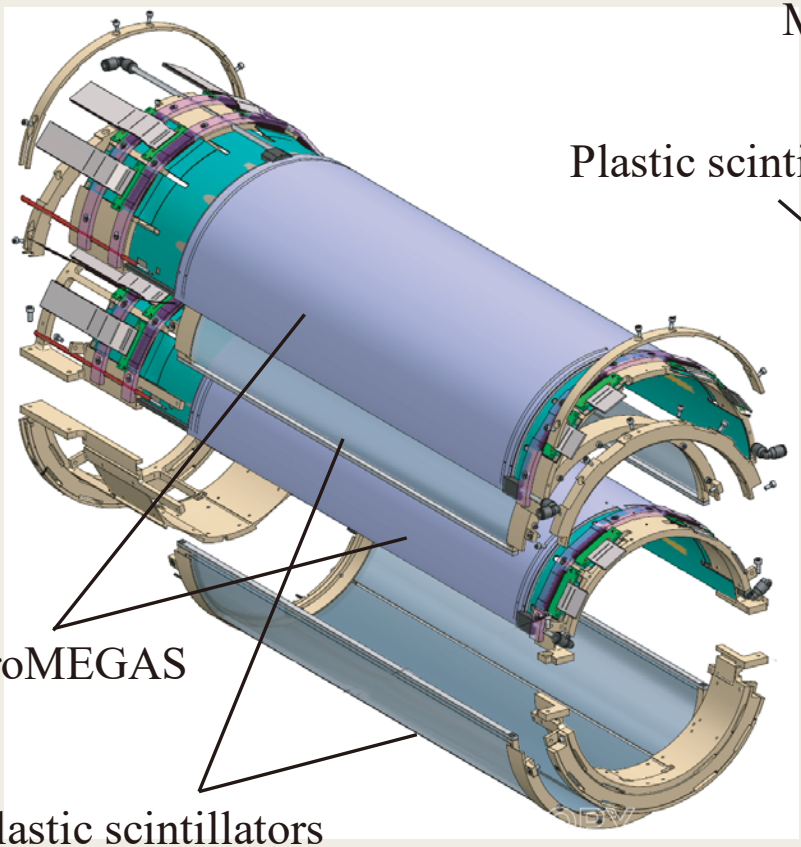
e^+

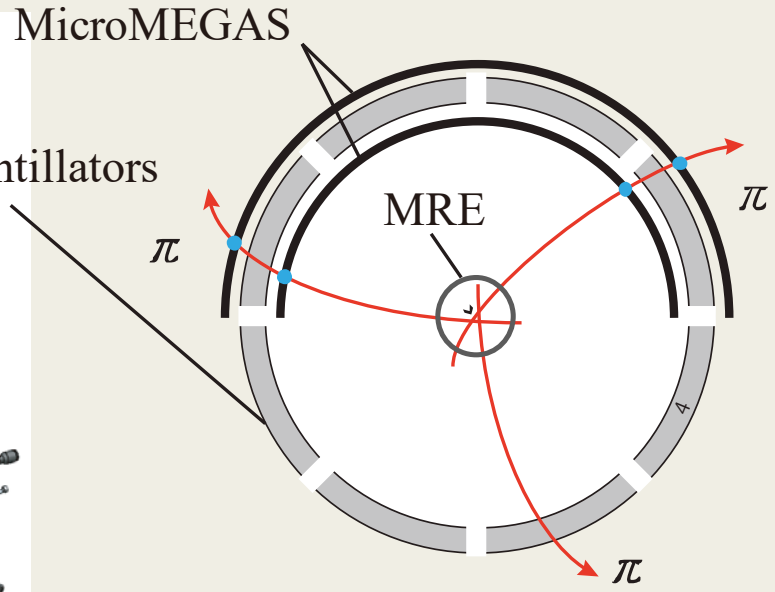
ASACUSA microm egas tracker (AMT)



Multi-ring electrodes

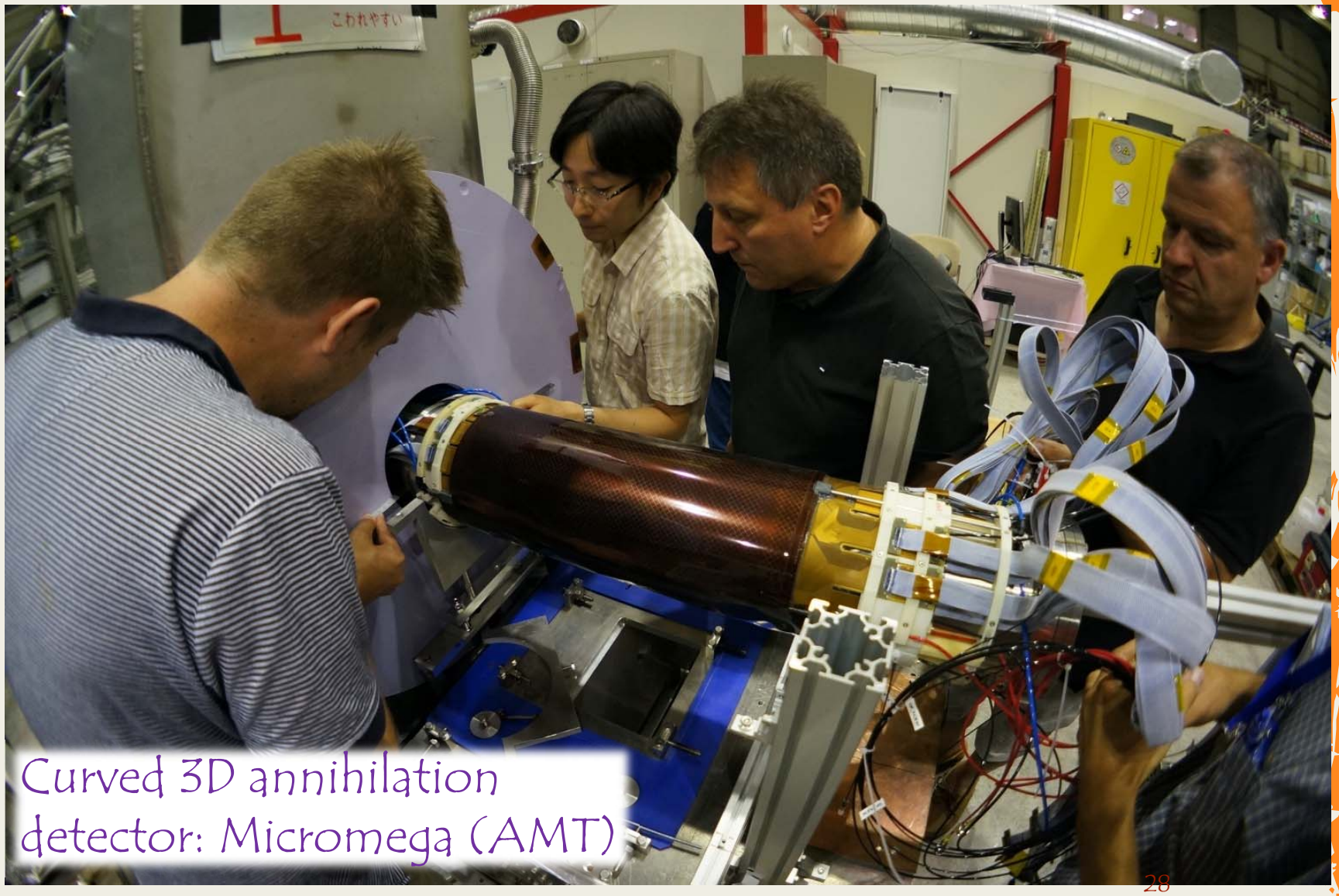
ASACUSA Miromegas Tracker (AMT)





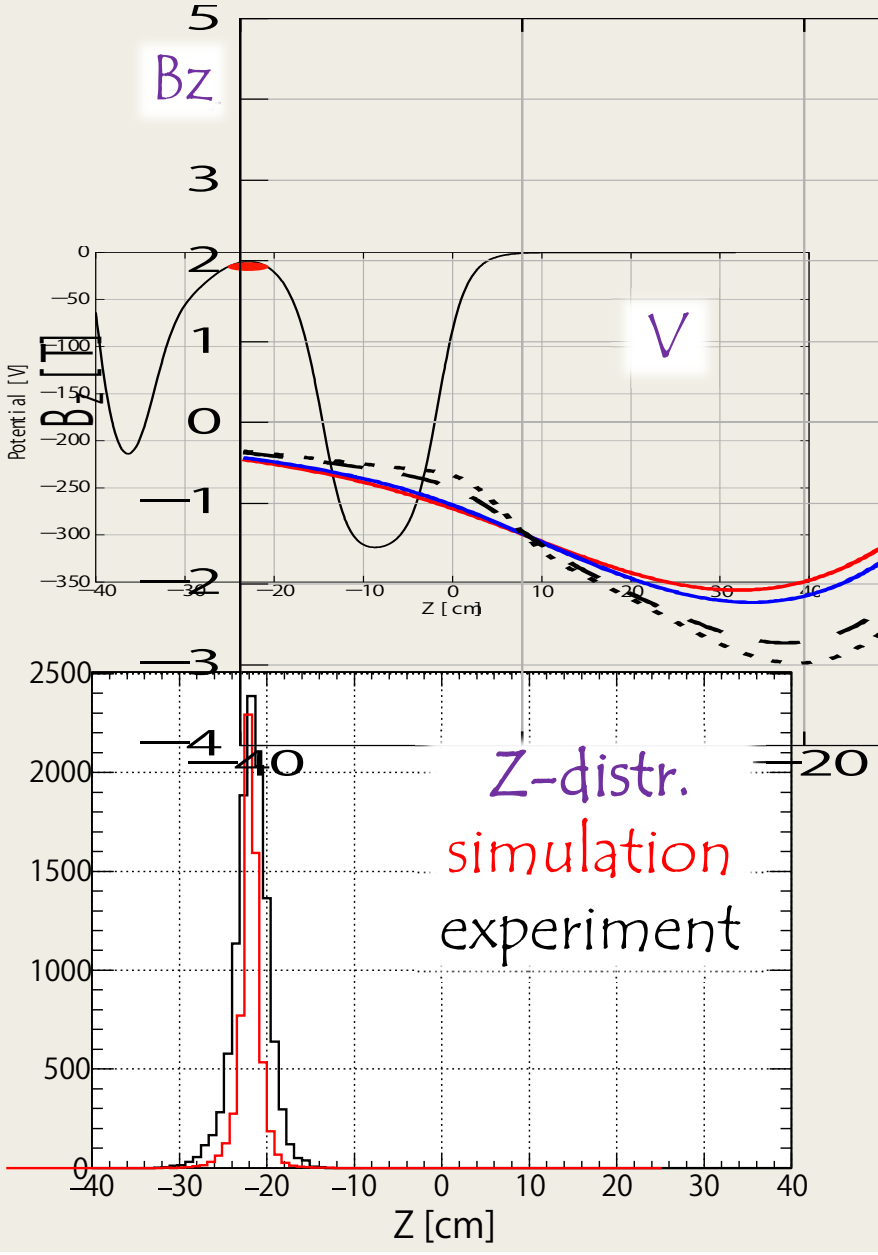
Size: radius =78.5mm, length=400mm
radius =88.5mm, length=400mm
Strips: 288 axial and 448 circumferential
Resolution: 250 μm

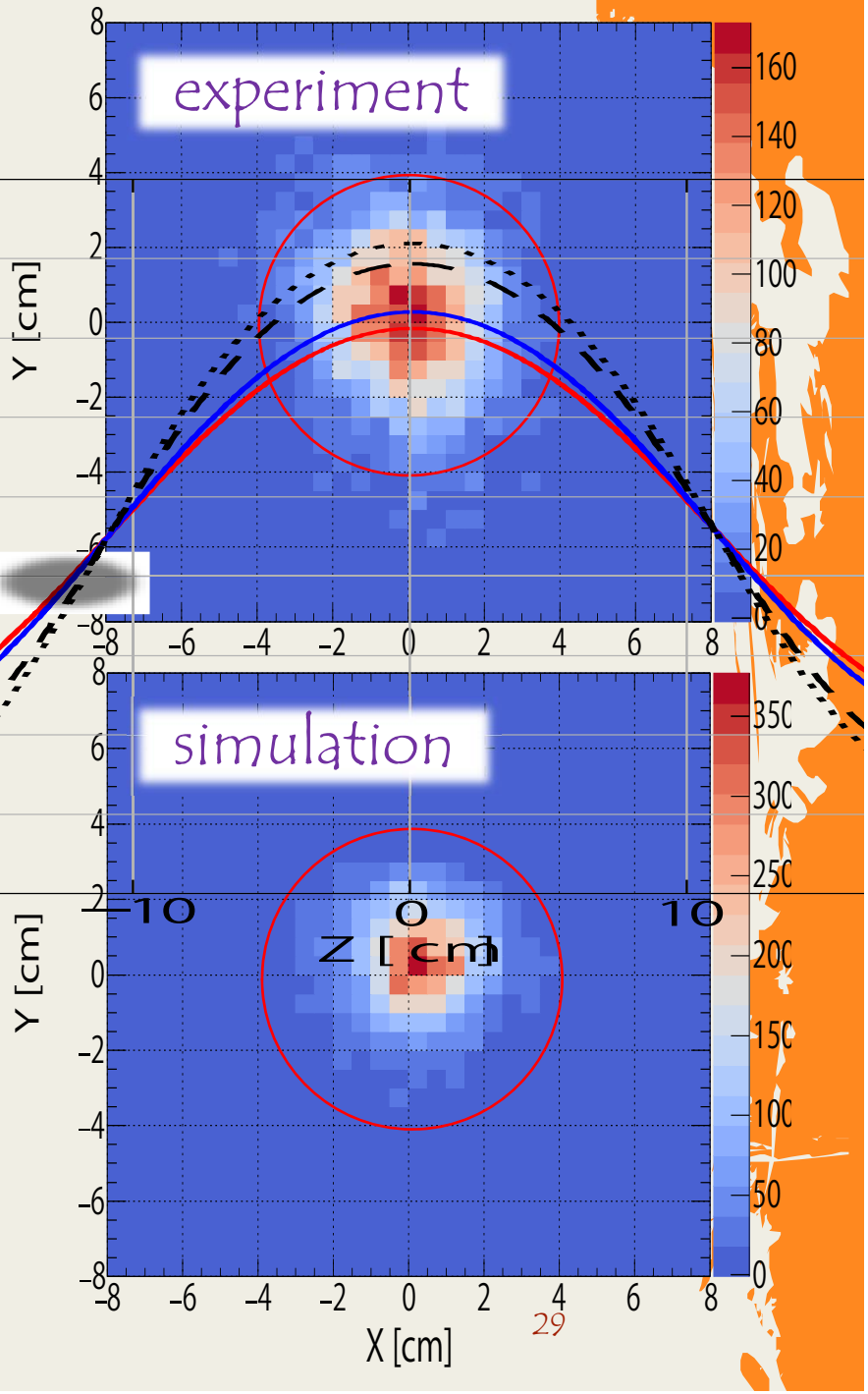
ASACUSA Miromegas Tracker (AMT)



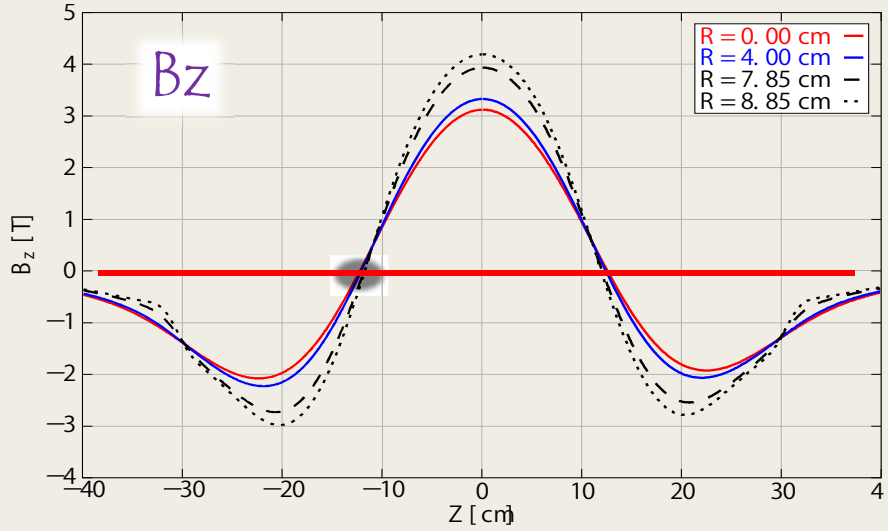
Curved 3D annihilation detector: Micromega (AMT)

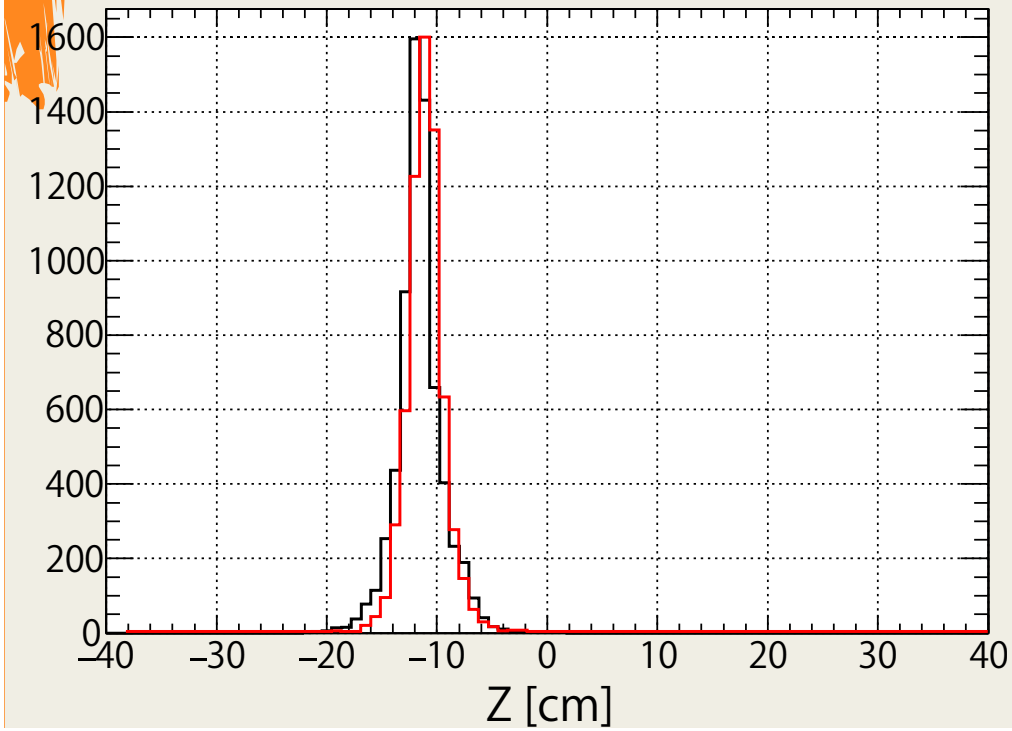
Test results: $\bar{p}$ annih.

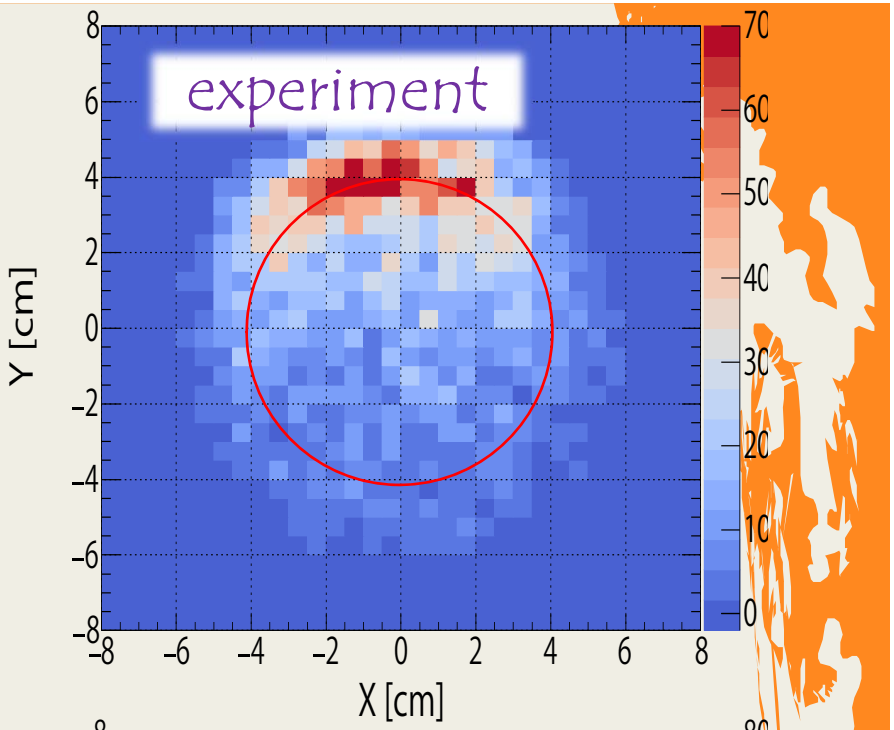


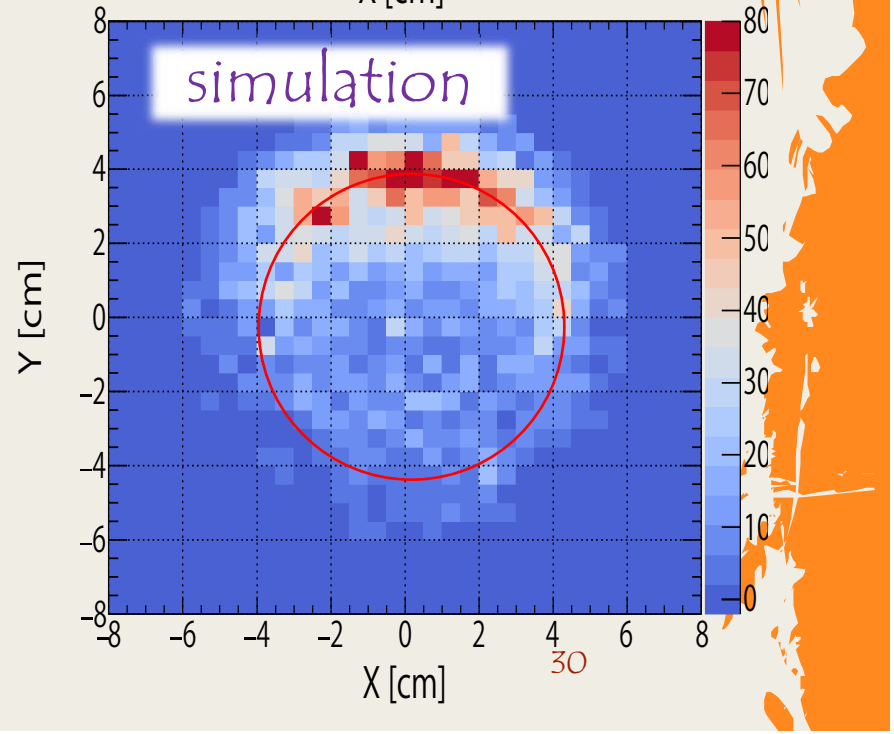


Test results: $\bar{p}$ annih.

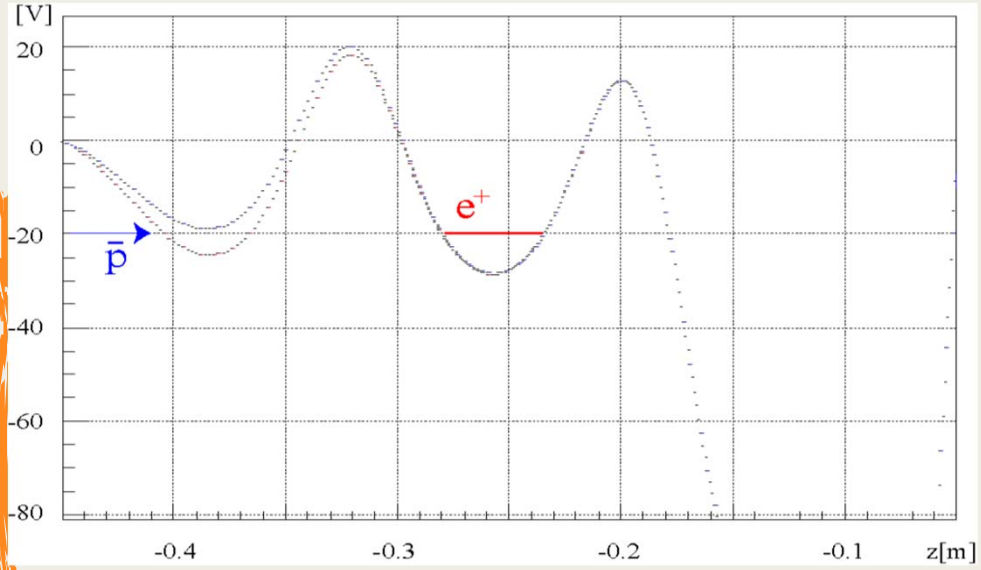


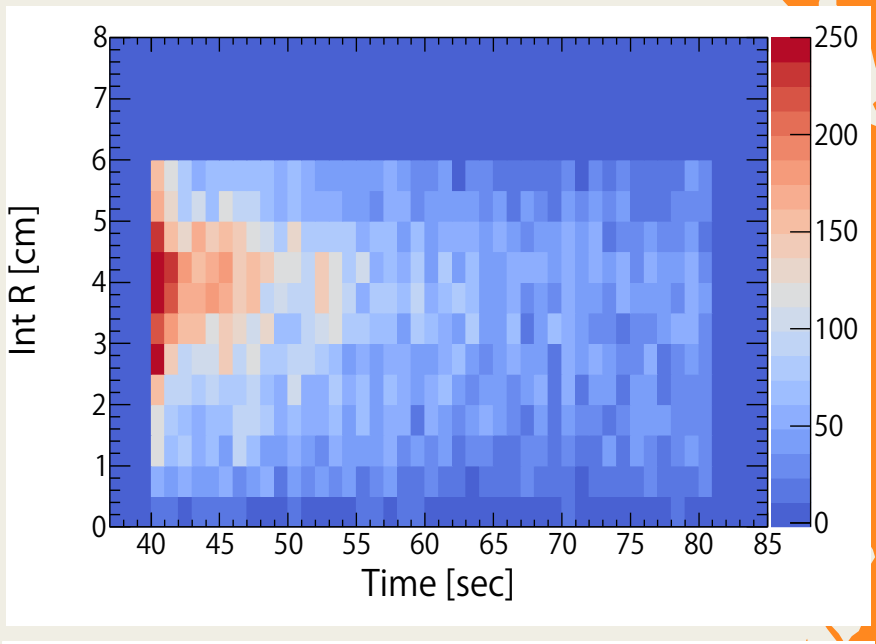


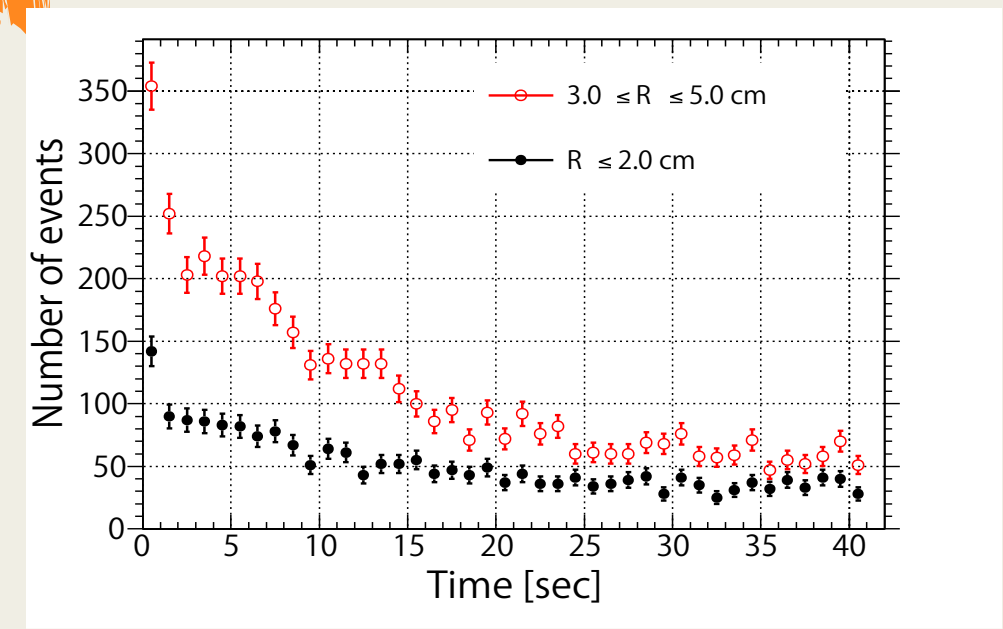


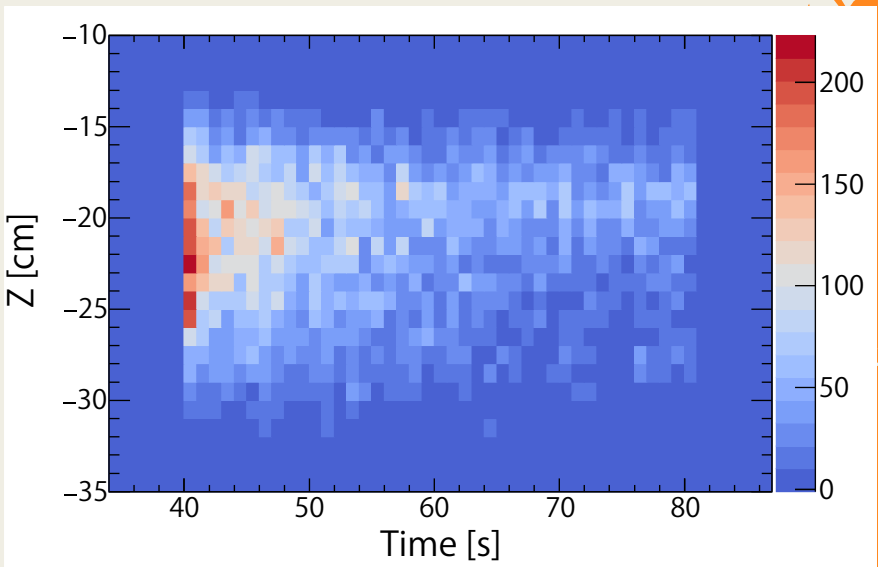


Mixing: $\bar{H}$ & $\bar{p}$ annih.

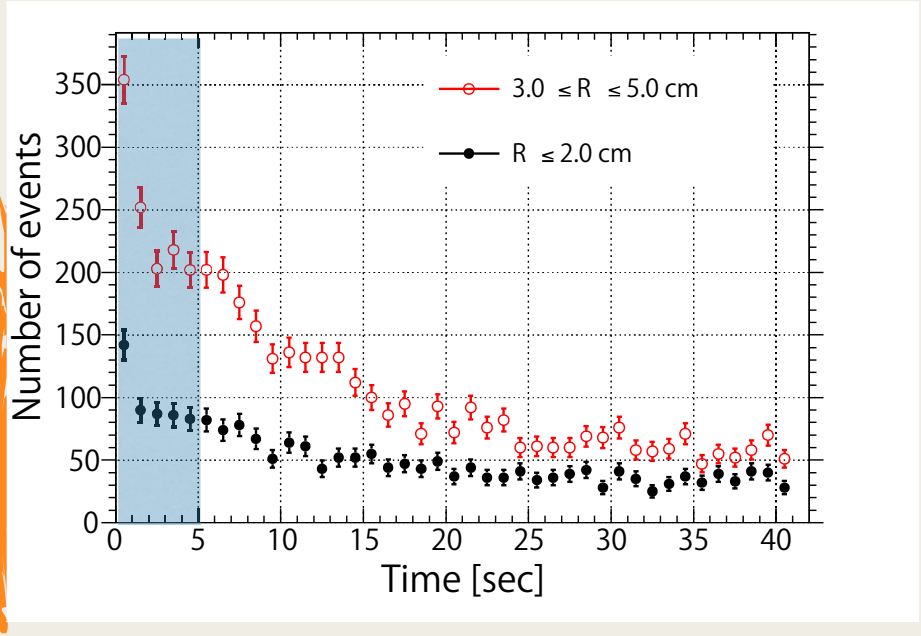


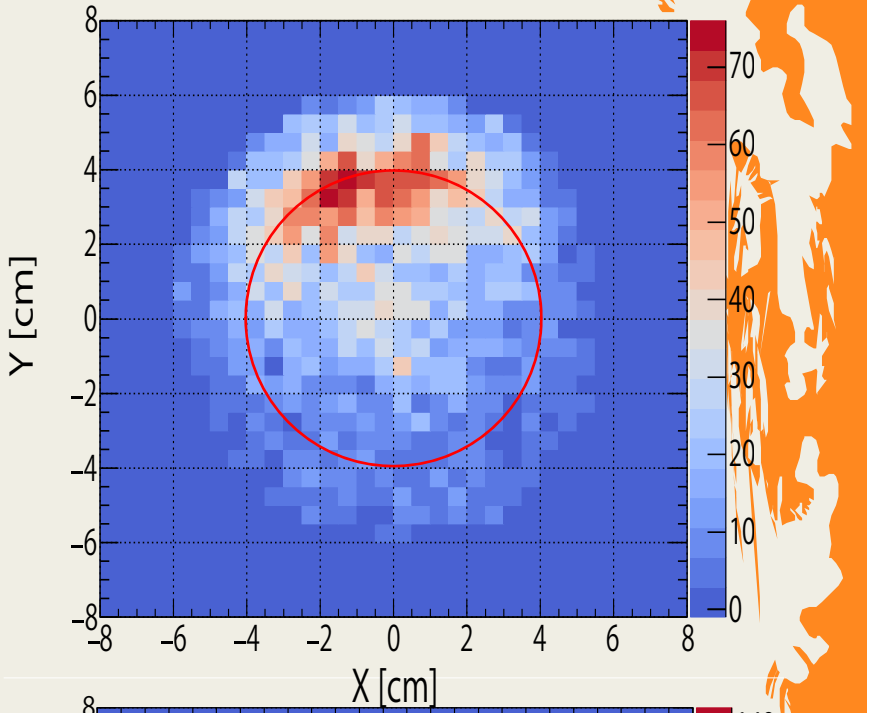


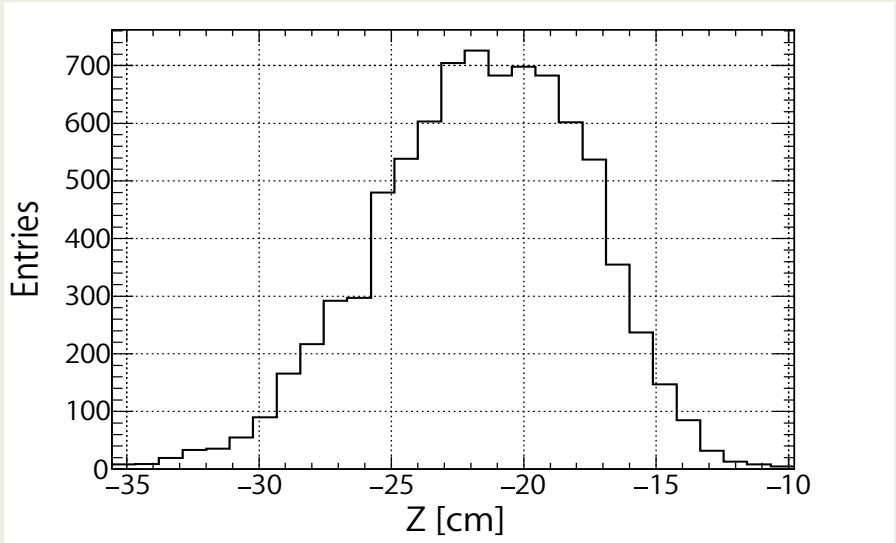


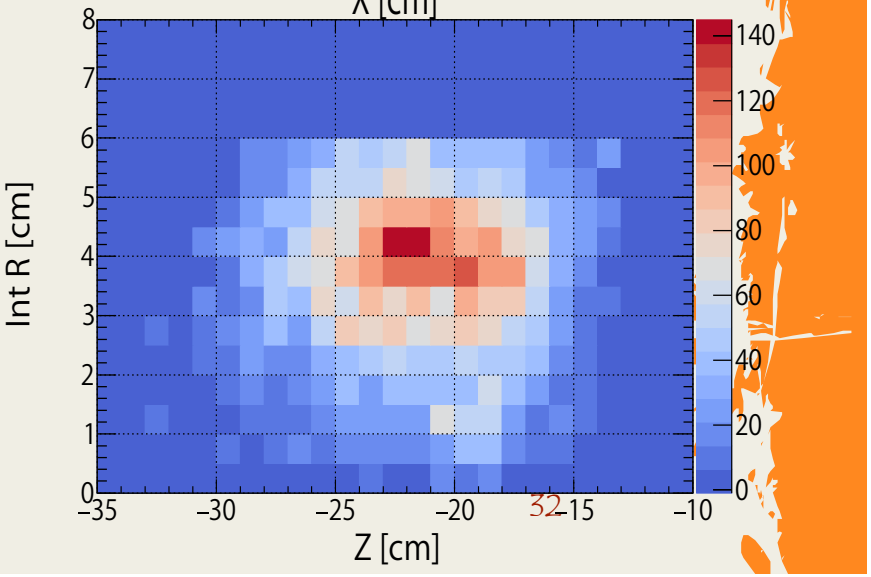


Mixing: $\bar{H}$ & $\bar{p}$ annih.

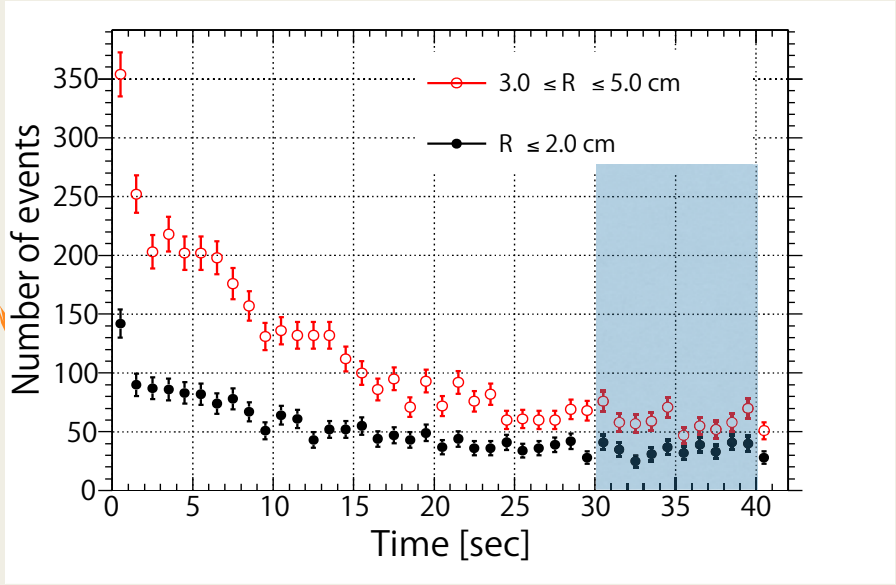


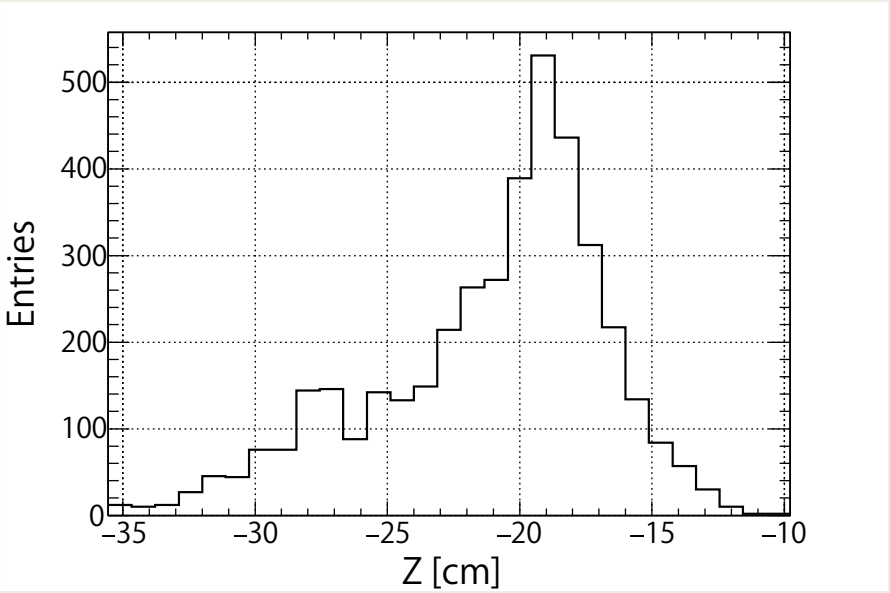


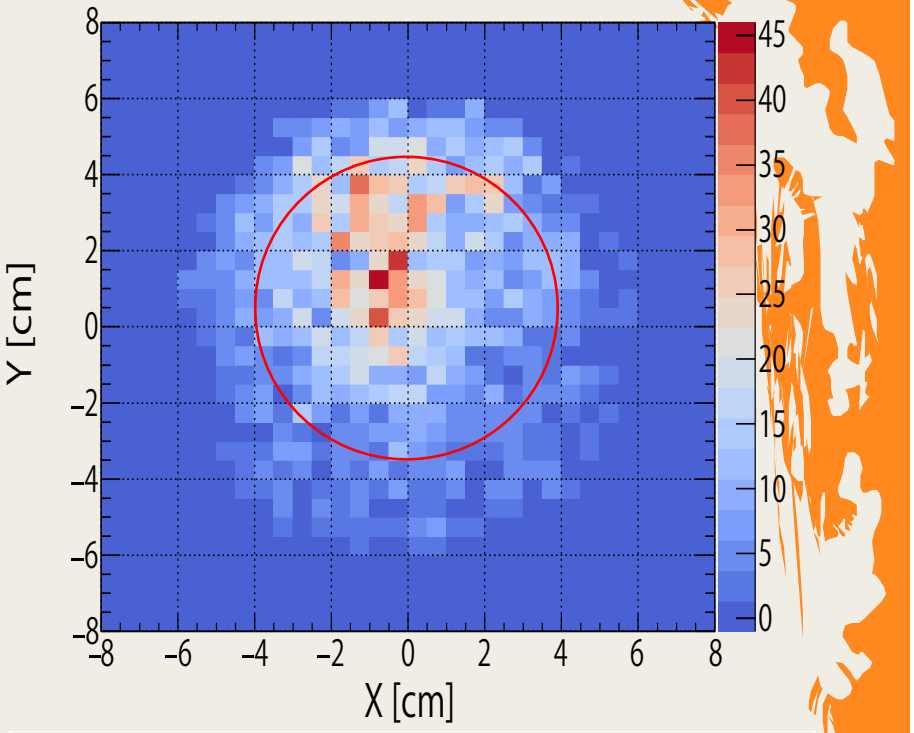


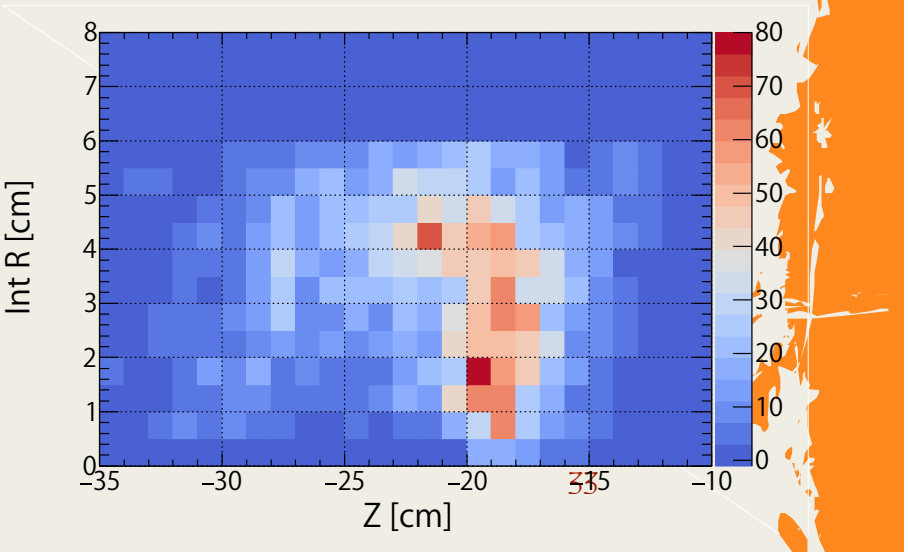


Mixing: $\bar{H}$ & $\bar{p}$ annih.

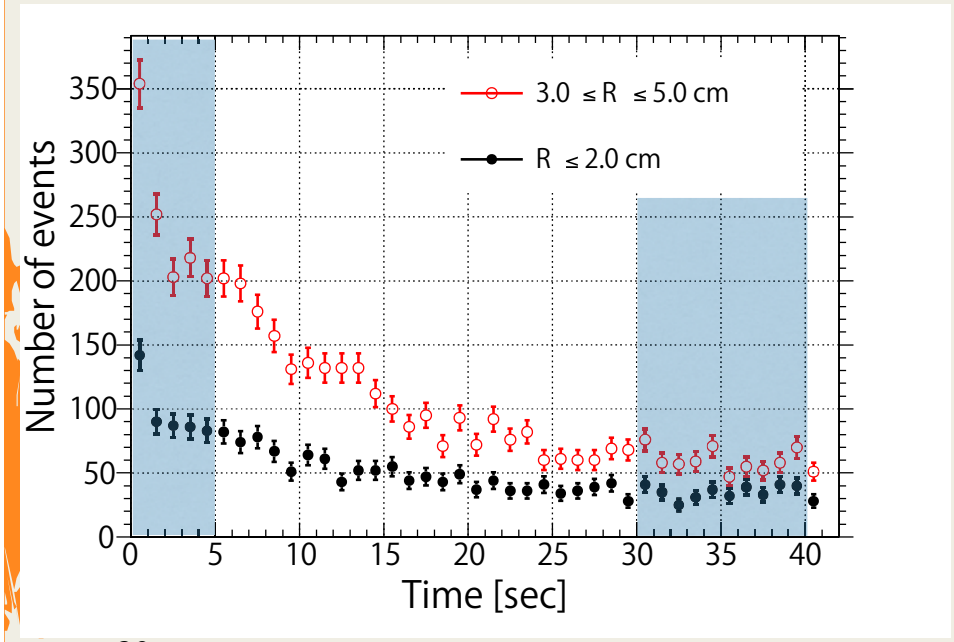


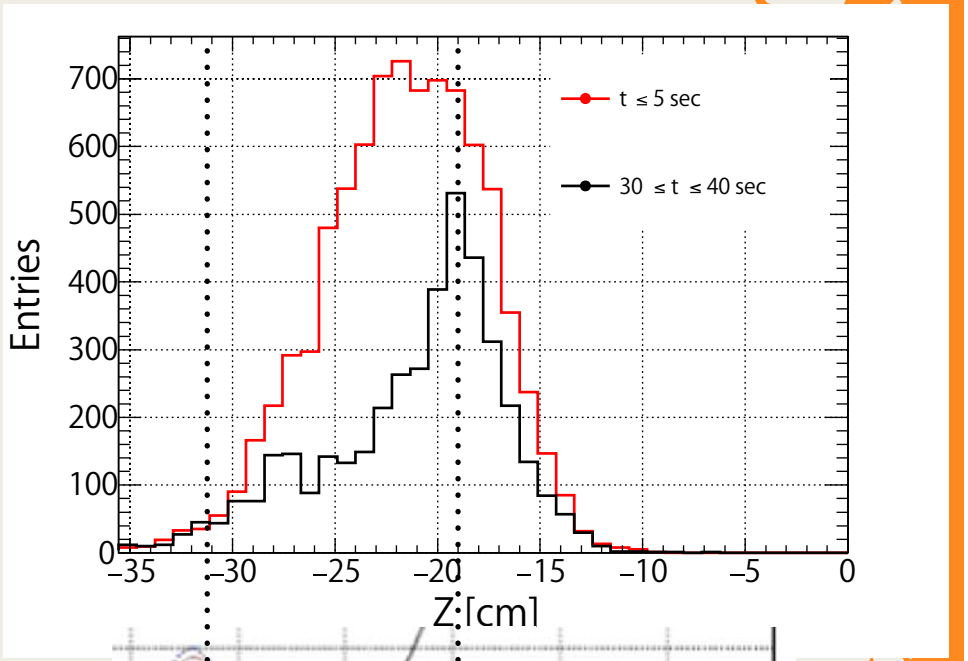


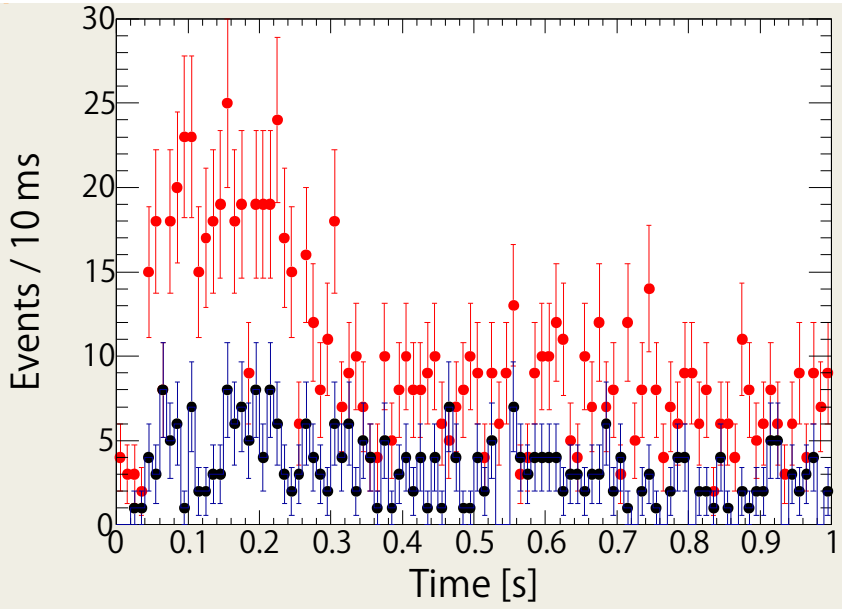




Mixing: $\bar{H}$ & $\bar{p}$ annih.

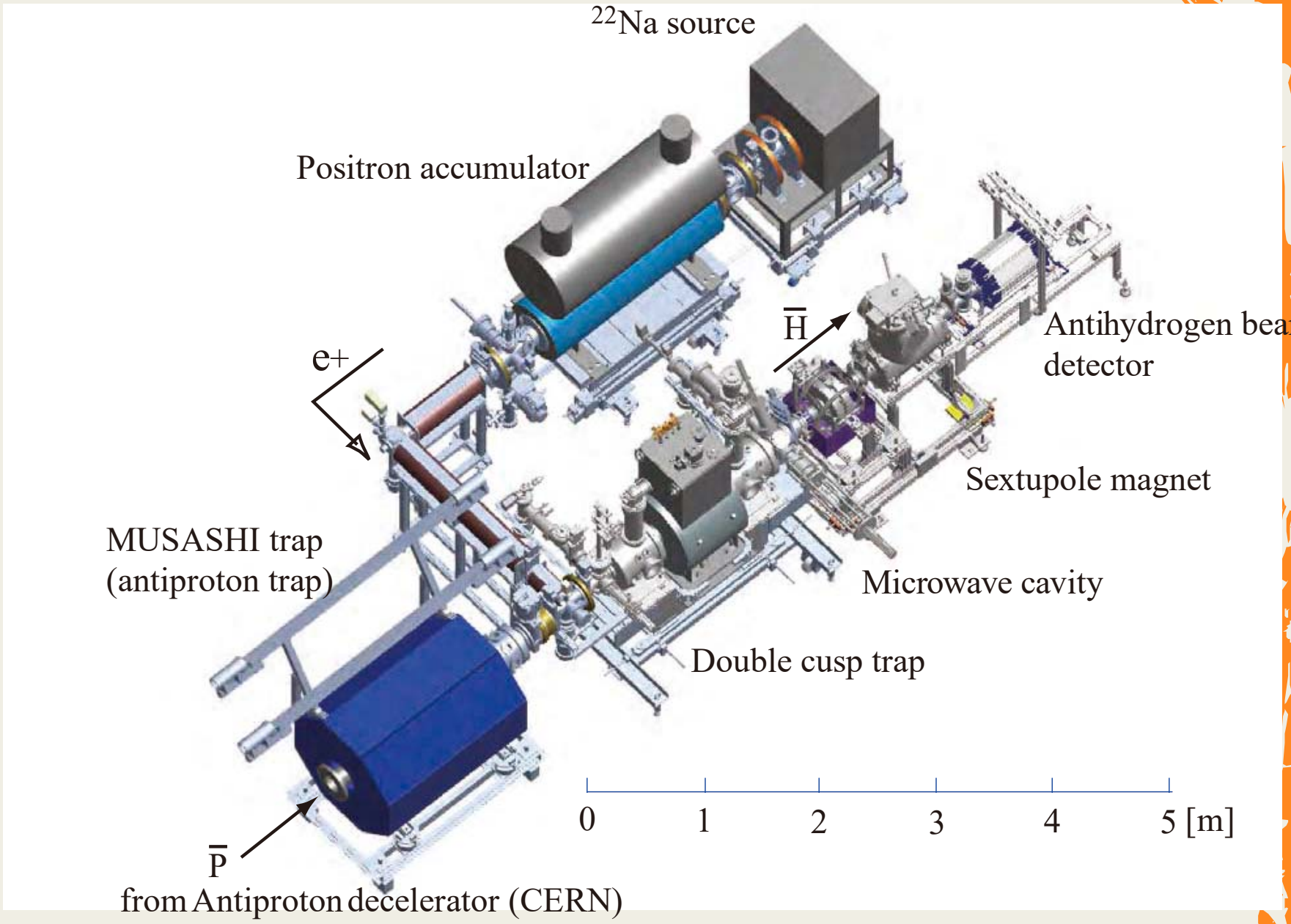






→ AMT works quite good!

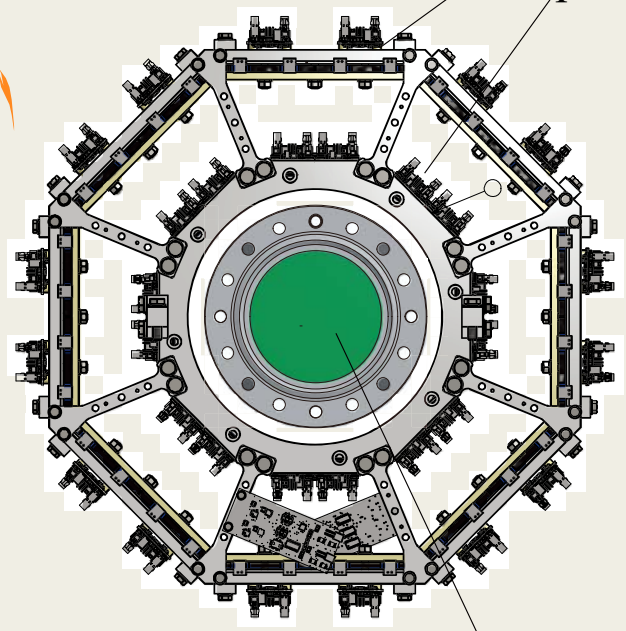
Double cusp magnet for polarized $\bar{H}$ beam



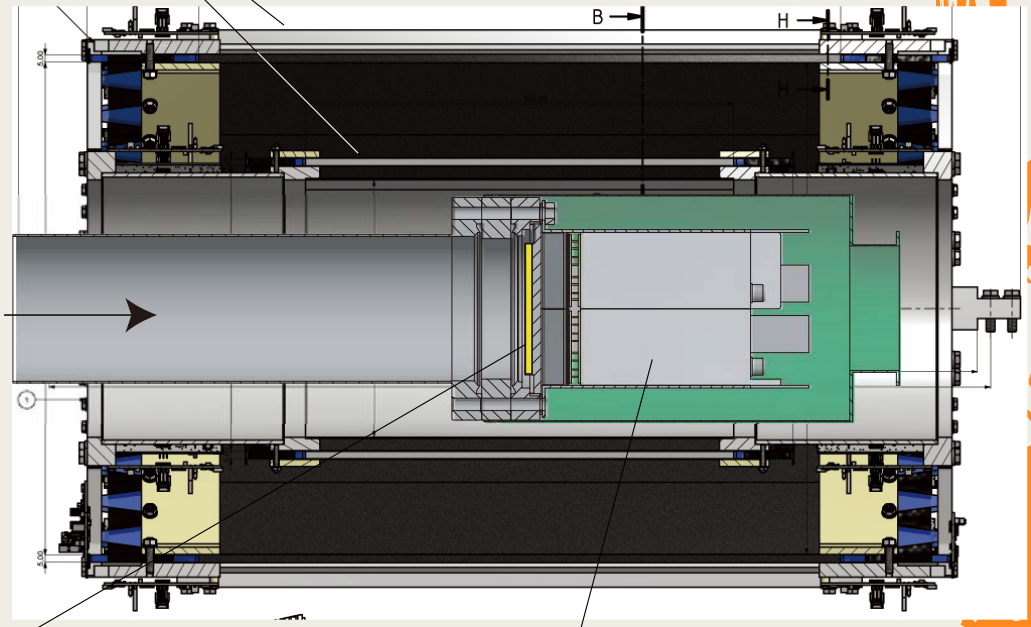
New $\bar{H}$ beam detector

Hodoscope

4 x 8 x 2 plastic scinti.



$\bar{H}$



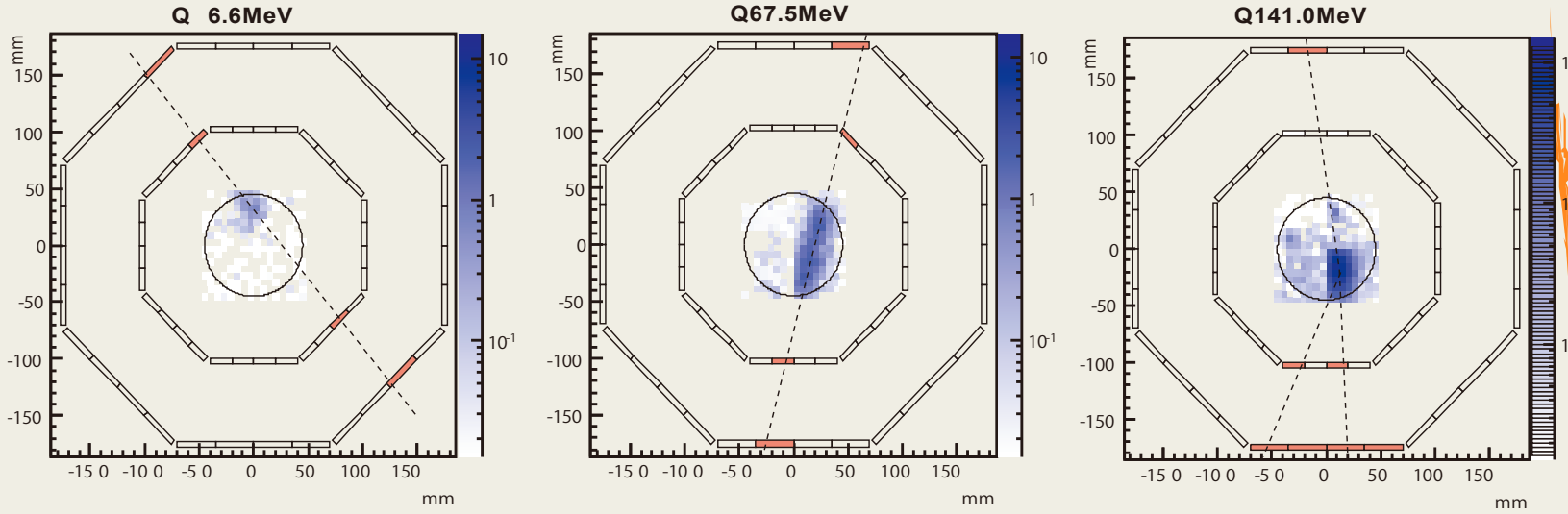
BGO disc

2D read-out PM

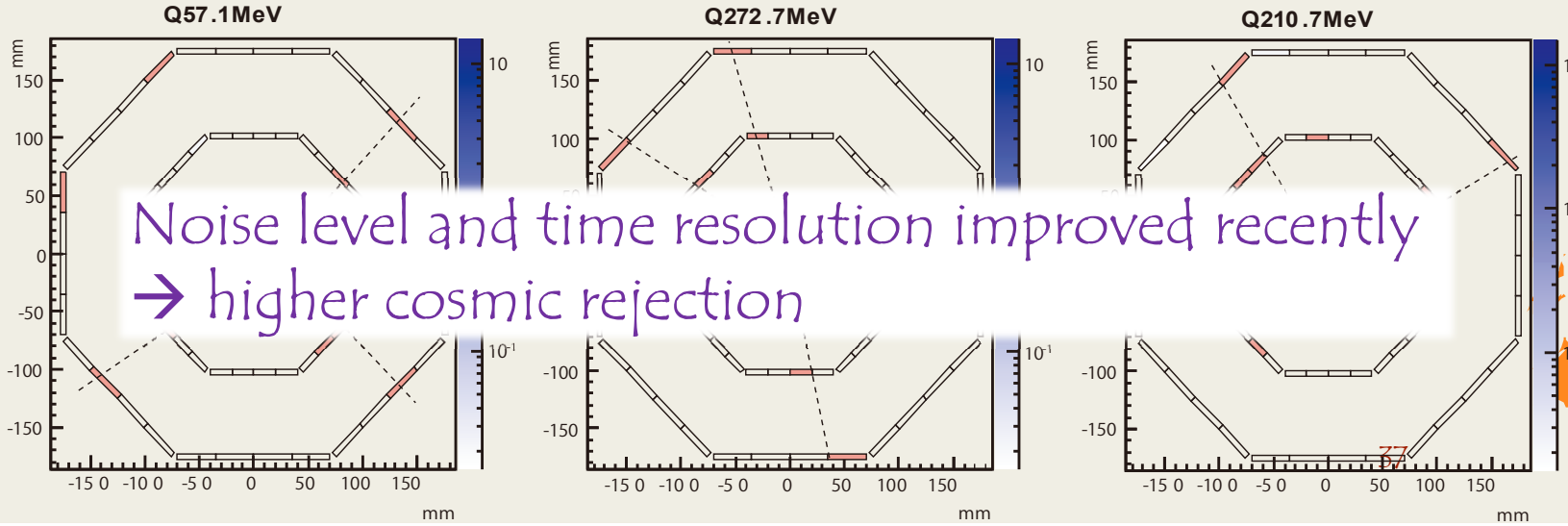
Refraction index of BGO~ 2.15→position sensitive read-out

New $\bar{H}$ beam detector

Cosmic ray

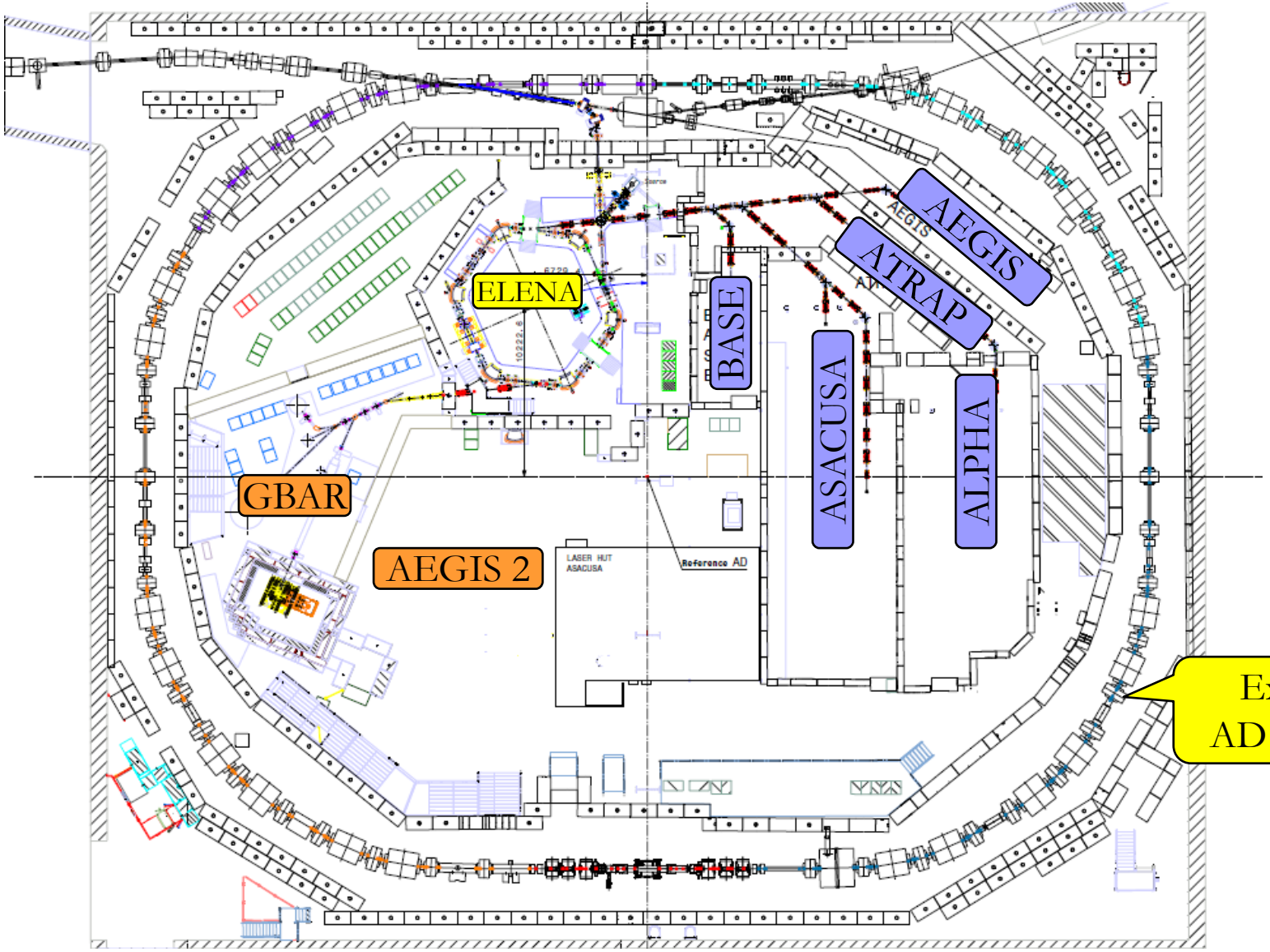


Antiproton



Noise level and time resolution improved recently
→ higher cosmic rejection

ELENA in CERN AD hall



Summary and Outlook

☆ Cold $\bar{H}$ beam employing the (double-)cusp scheme is in progress

☆ AMT works good!

☆ $\bar{H}$ spectroscopy HF starts hopefully this year

☆ ELENA construction sometime soon → Two beamlines

Antihydrogen research

Chinese red

Thank you very much for your attention!

A robber family who steals precious Chinese red from King's grave digging a long tunnel for many generations

Now we are at the entrance of the real antihydrogen research!