@ ALPHA/CERN

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LASER IF-UFRJ

CLC - PSAS'08

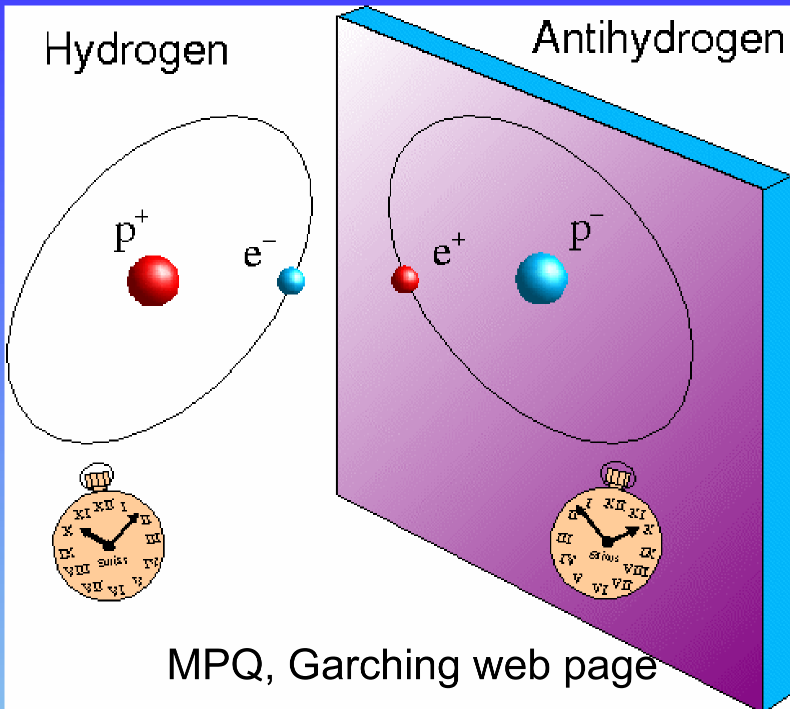
FAPERJ

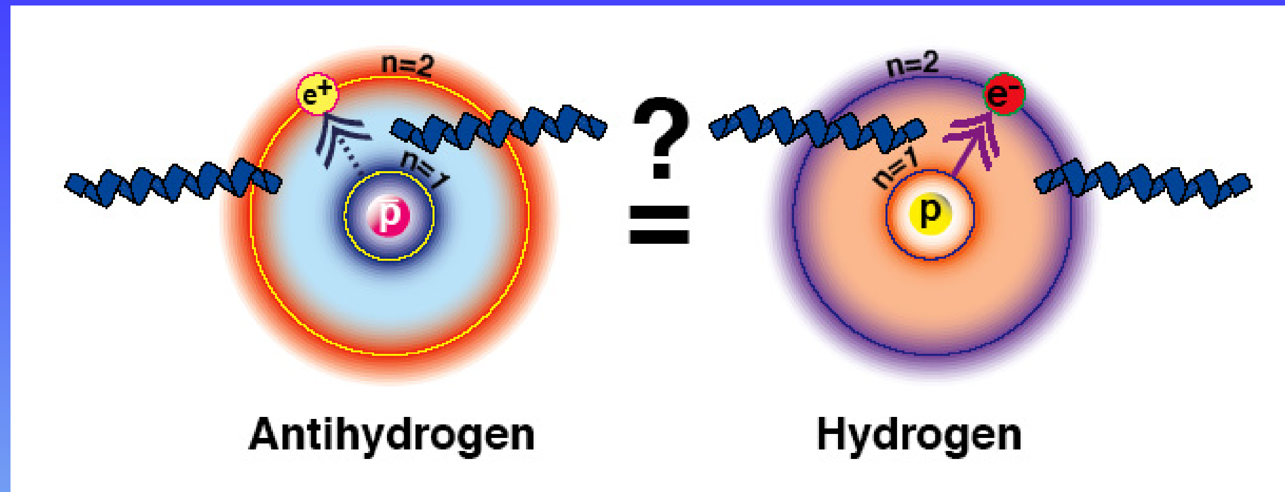
FINEP
FINANCIADORA DE ESTUDOS E PROJETOS

CNPq
Conselho Nacional de Desenvolvimento

ANTIHYDROGEN

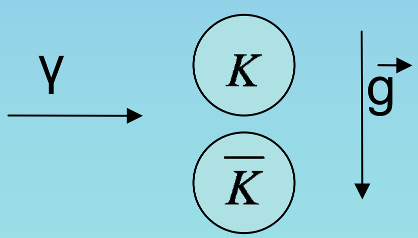
1 - CPT theorem, base of the Standard Model:





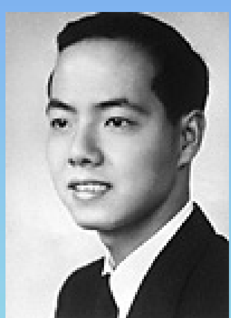
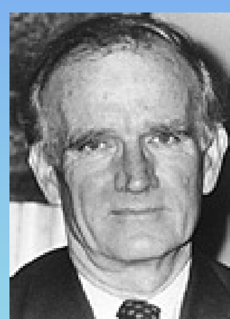
"CPT and Lorentz Tests in Hydrogen and Antihydrogen", Robert Bluhm, V. Alan Kostelecký, and Neil Russell, PRL 82, 2254 (1999)

2 - Relativity □ Equivalence Principle



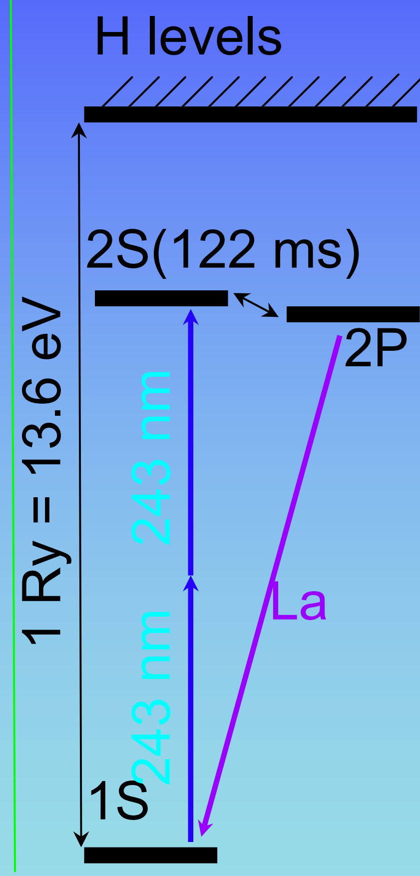
"Motivations for antigravity in General Relativity", G.Chardin, Hyp. Interact. 109, 83 (1997)

Antihydrogen: + motivation

P violation:	CP violation:
 C. Yang 1957	 J. Cronin 1980
 T.D.Lee 1957	 V. Fitch 1980

HYDROGEN (1S-2S):

fundamental: 14 significant digits, QED, Lamb Shift, cosmological variation of fundamental constants, proton form factor!



"Two-Photon Spectroscopy of Trapped Atomic Hydrogen", Claudio L. Cesar, Dale G. Fried, Thomas C. Killian, Adam D. Polcyn, Jon C. Sandberg, Ite A. Yu, Thomas J. Greytak, and Daniel Kleppner, John M. Doyle, PRL 77, 255 (1996)

"Measurement of the Hydrogen 1S-2S Transition Frequency by Phase Coherent Comparison with a Microwave Cesium Fountain Clock", M. Niering, R. Holzwarth, J. Reichert, P. Pokasov, Th. Udem, M. Weitz, and T. W. Hänsch, P. Lemonde, G. Santarelli, M. Abgrall, P. Laurent, C. Salomon and A. Clairon, PRL 77, 5496(2000)

TABLE 1. Direct tests of CPT via particle-antiparticle comparisons [Particle Data Group - with updates] (from Fujiwara et al. PBAR08)

Particle, CPT quantity	Relative precision	Δm in energy (GeV)
$e^- \, e^+$ mass	0.8×10^{-8}	4×10^{-12}
$\bar{p}$ p mass	2×10^{-9}	2×10^{-9}
$e^- \, e^+$ g-2	2×10^{-9}	
$\mu^- \, \mu^+$ g-2	0.7×10^{-6}	
$\bar{p}$ p q/m	0.9×10^{-10}	
$\bar{p}$ p mag.mom.	3×10^{-3}	
$\bar{K}_0 \, K_0$ mass	10^{-18} *??	

Colaboração ATHENA

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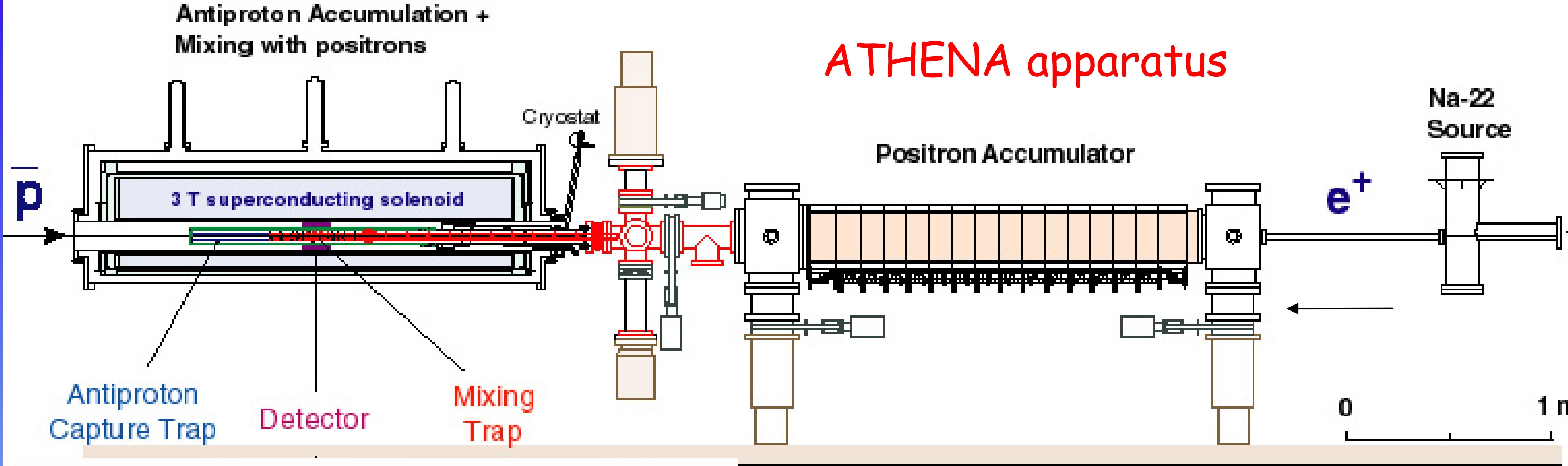
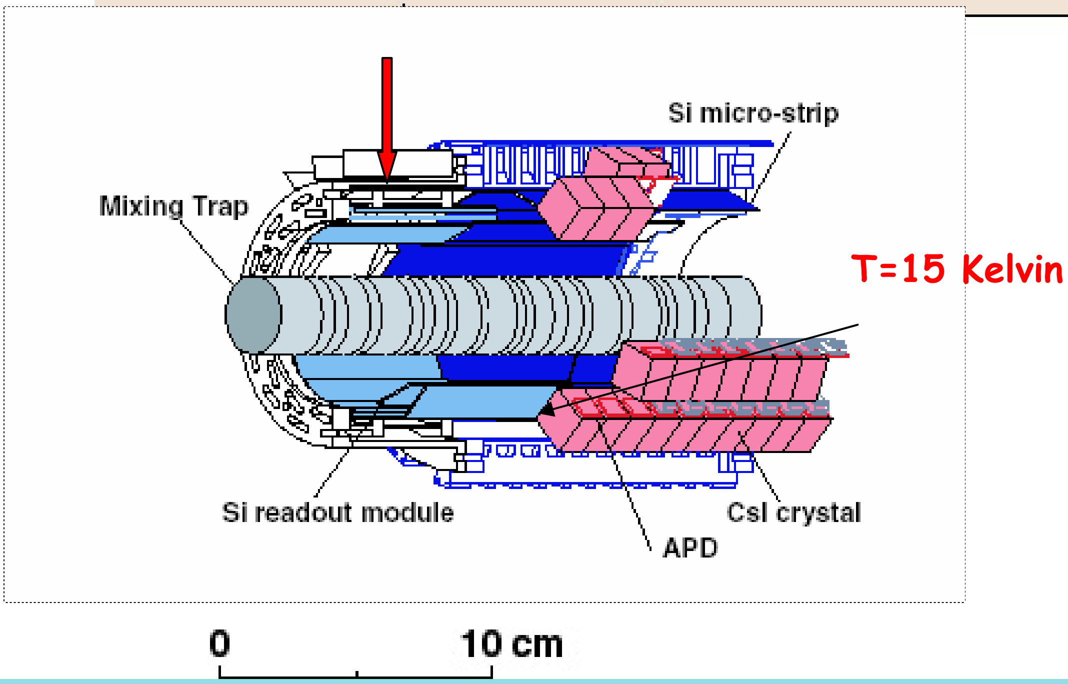
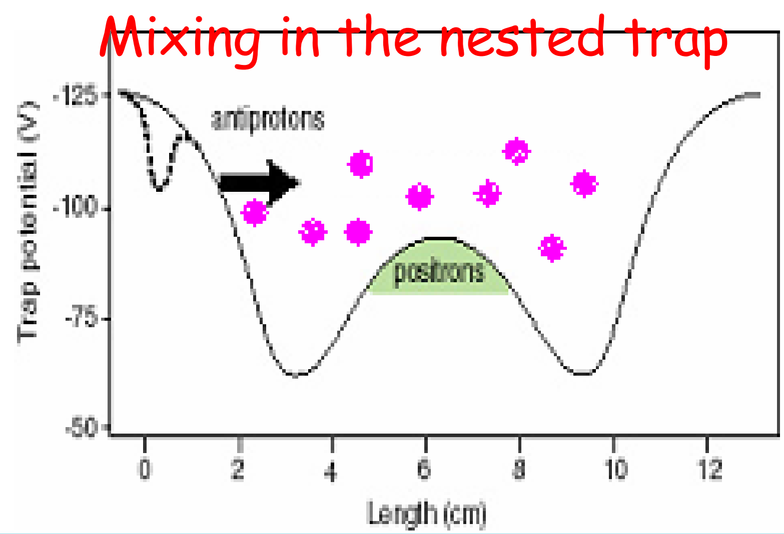
Ist. Naz. Fisica Nucl. and Univ. of Brescia, Genova, Pavia (Italy)

C. Lenz Cesar

Fed. Univ. Of Rio de Janeiro (Brazil)

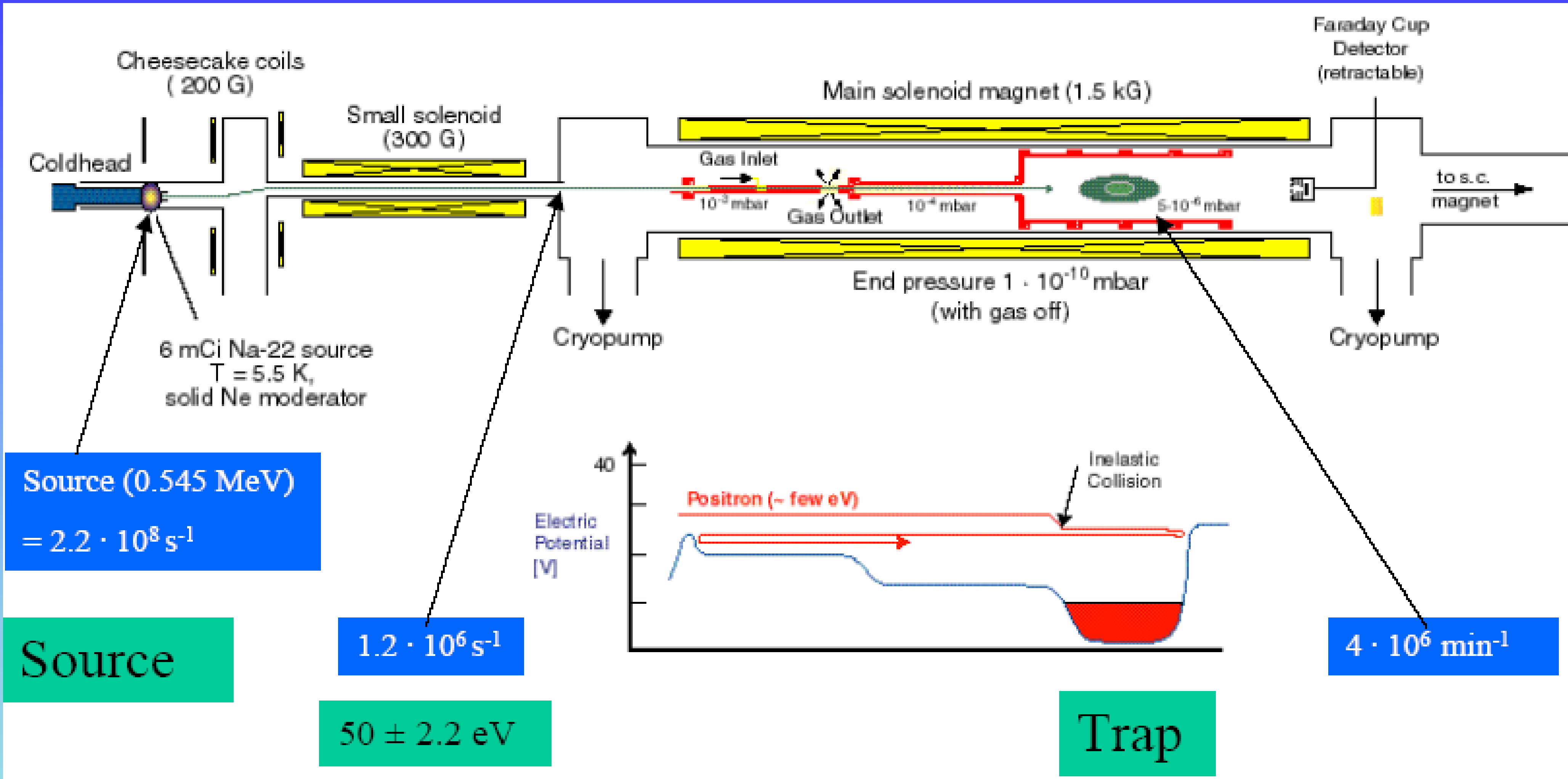






M. Amoretti et al (ATHENA COLLABORATION) NIM A 518 (2004) 679

Pósitron (e+) Accumulator: Penning Trap and Buffer Gas



Pósitron Plasma

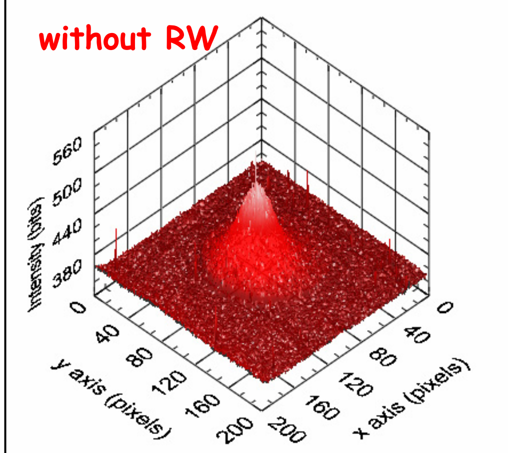
2003 run: More positrons and higher plasma density

Upgrading during 2003

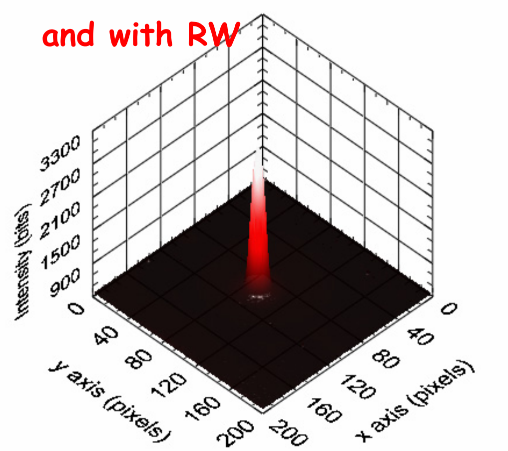
- Phosphor screen + CCD in place of the Faraday cup in the accumulator
- Stacking of several positron shots in the mixing trap
- Rotating wall in the mixing trap: control of the plasma density before mixing using the improved diagnostic

Images of positrons in the accumulator:

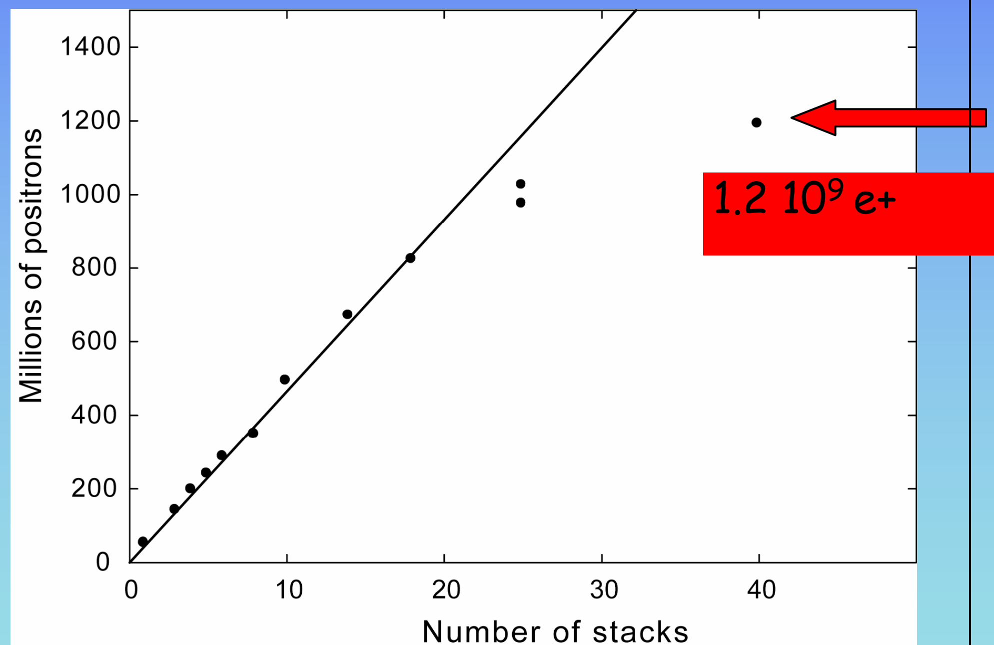
without RW



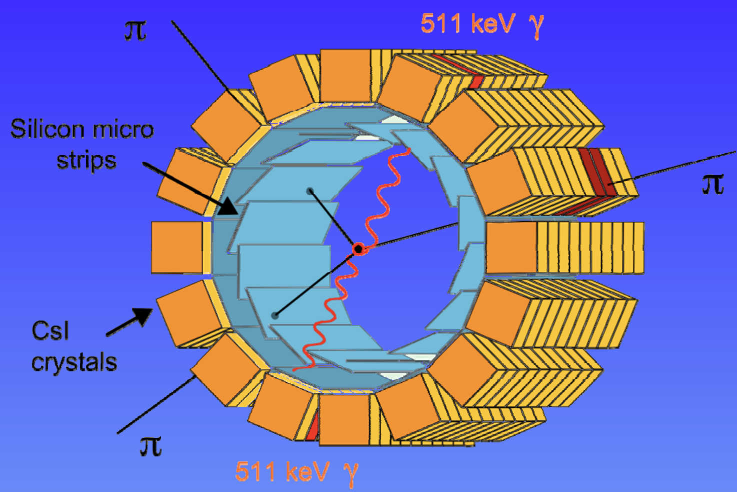
and with RW



Positrons stacking in the mixing trap: 4.7 10^7 e^+/stack (200 sec/stack)



Antihydrogen detector



Vertex rec. eff.: 50%

Position resolution (∫): 4 mm

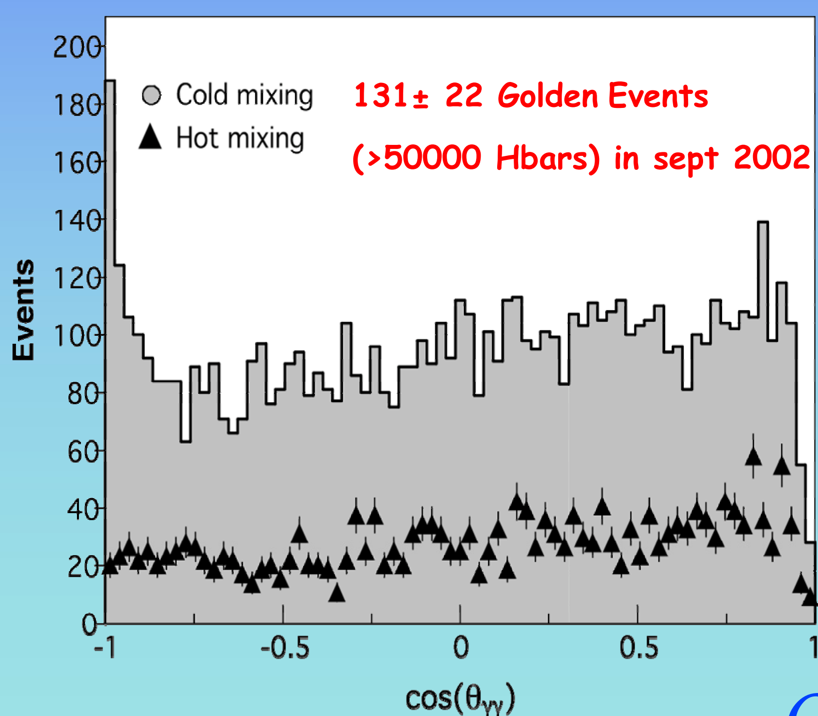
Silicon trigger efficiency: (85 +-10)%

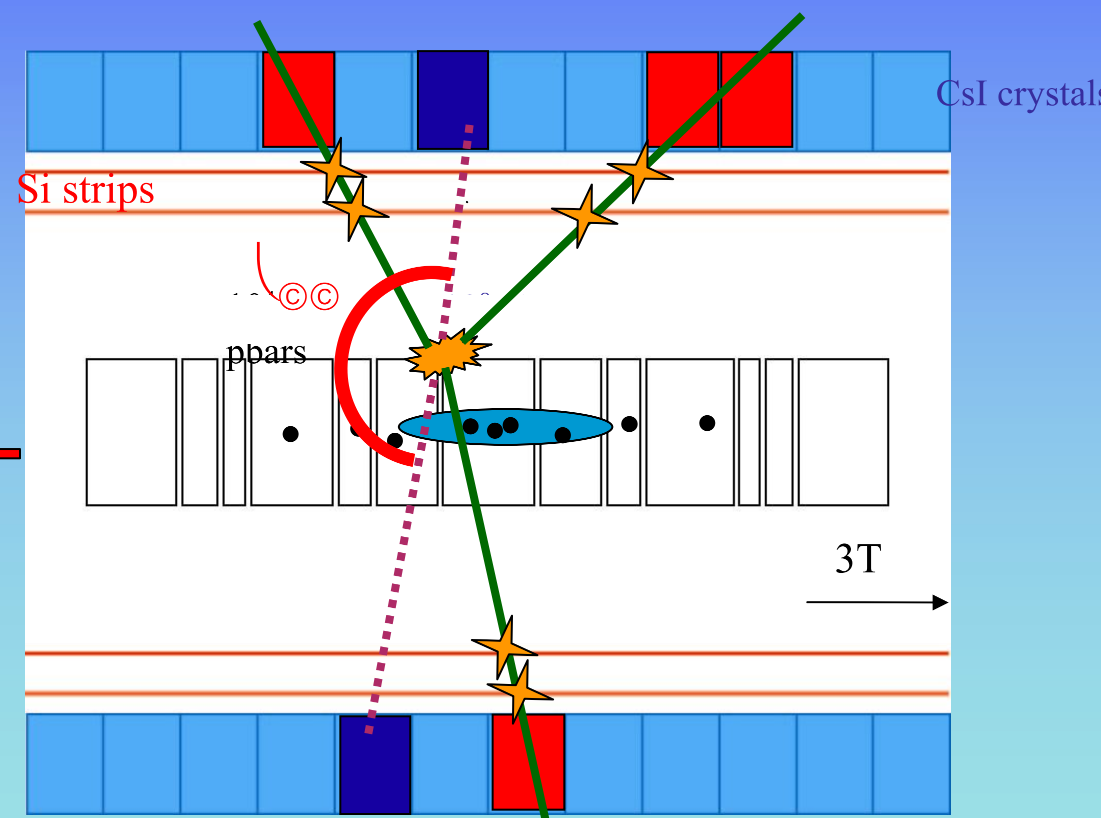
Photon energy resolution: 24% (FWHM) @ 511KeV

Photon detection efficiency: 20%

Full simulation by Montecarlo based on GEANT 3.21

Opening angle distribution





Amoretti et al.,(ATHENA coll.)***Nature*** 419 (2002) 456

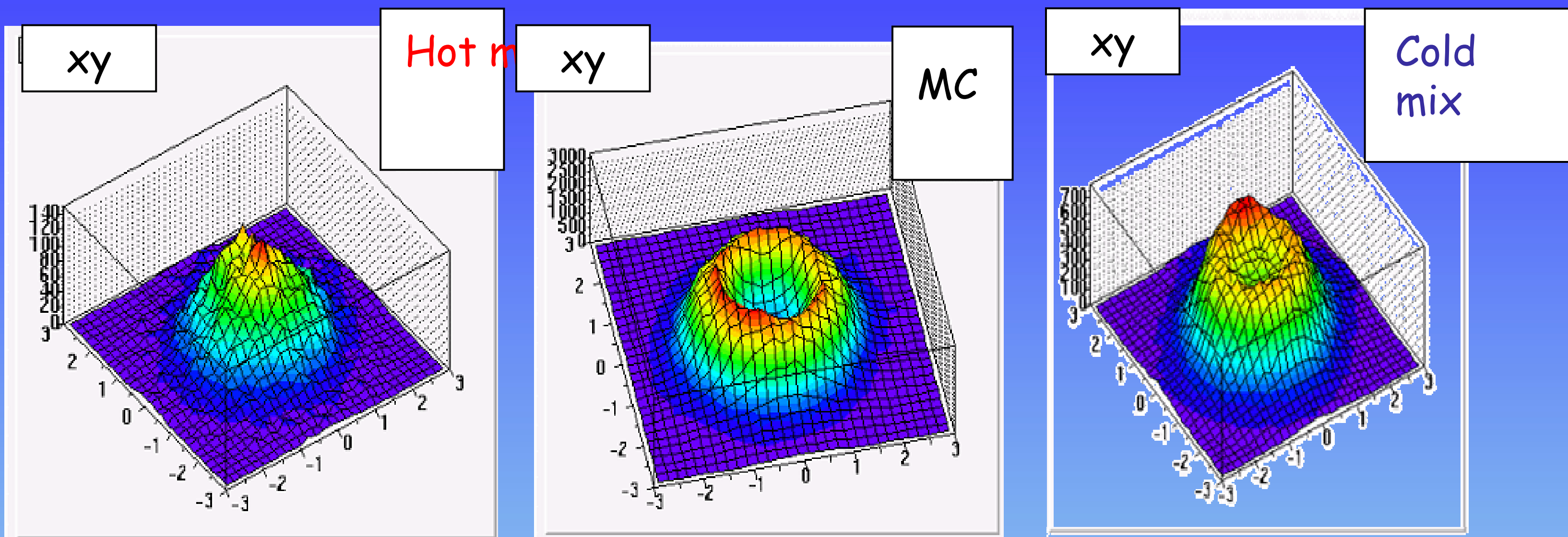
Beyond the golden events

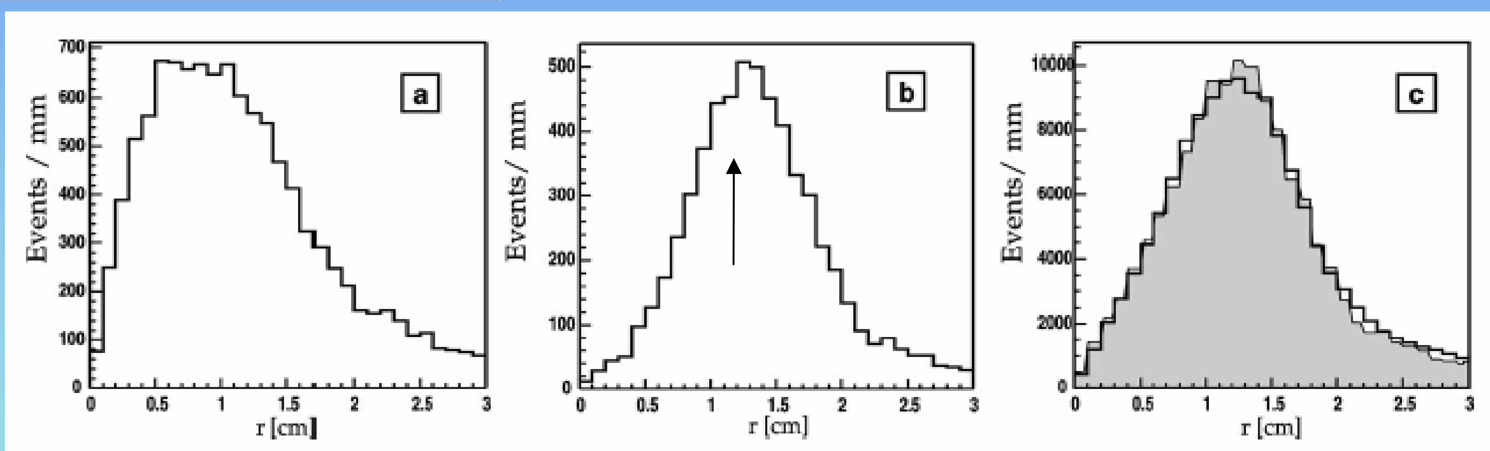
M. Amoretti et al. (ATHENA collaboration) Phys. Lett. B 578 (2004) 23

Further analysis using all the informations present in the data and the Montecarlo code

1. Vertex radial distribution 2. Full shape of the opening angle distribution

1) Vertex radial distribution fit





dn/dr hot mixing: annihilation around the trap center

dn/dr:annihilations on trap walls (MC or "pbar only")

dn/dr

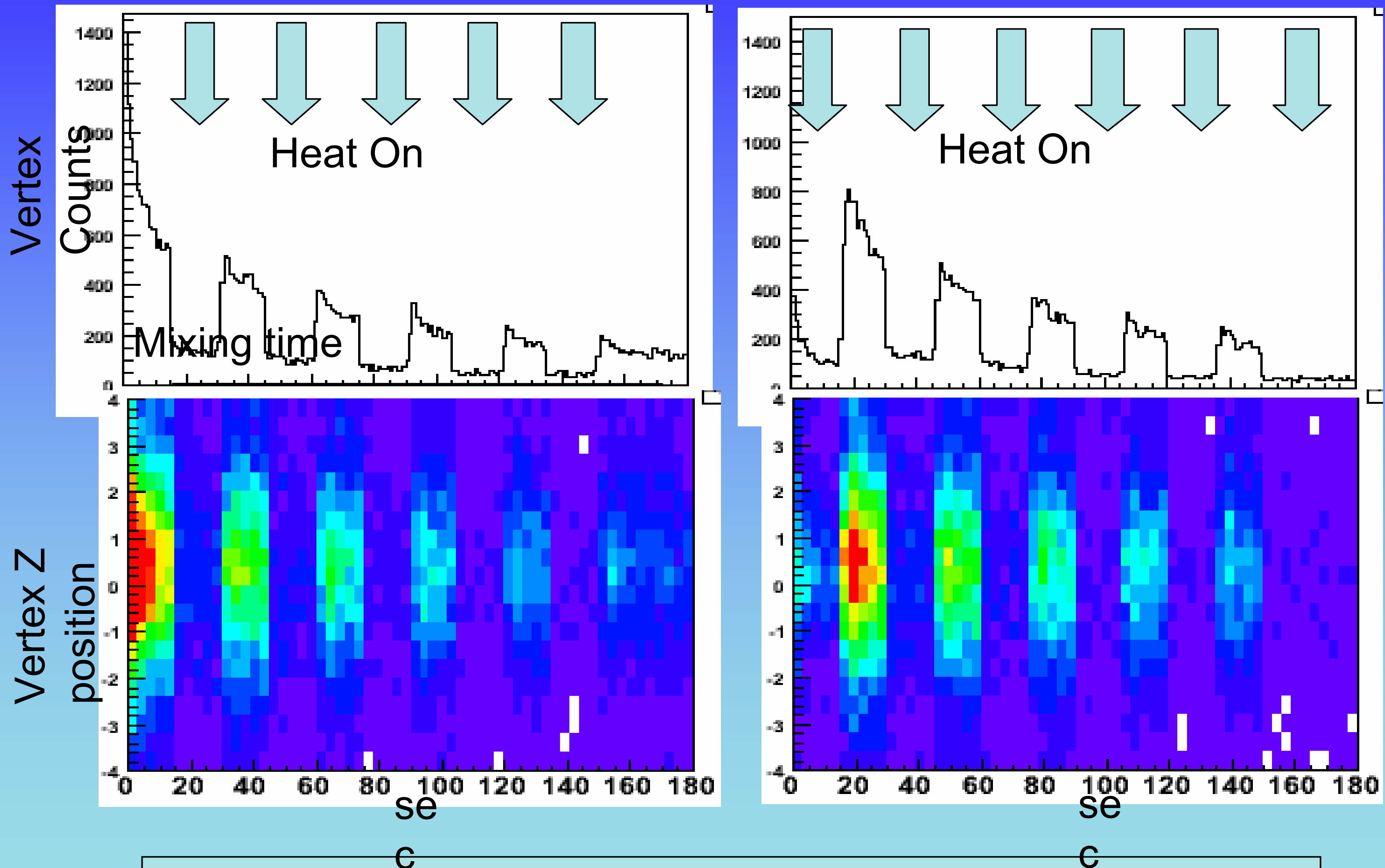
Cold mixing

$(69 \pm 1)\%$ $\bar{H}$

$(31 \pm 1)\%$ backg.

Controle da Formação de Antihidrogênio

RF heating of e+ to switch off formation



A Pulsed Source on Cold Antihydrogen !

Direcionalidade dos antihidrogênios

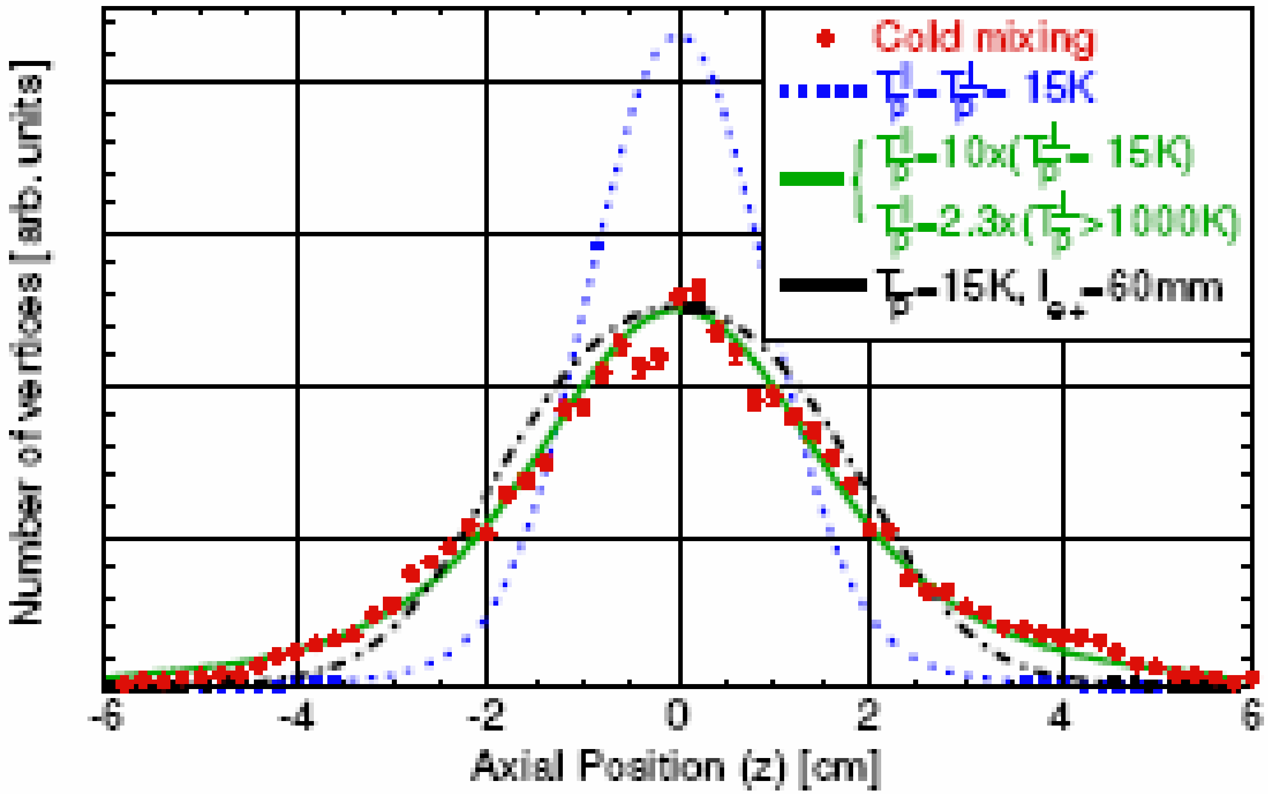
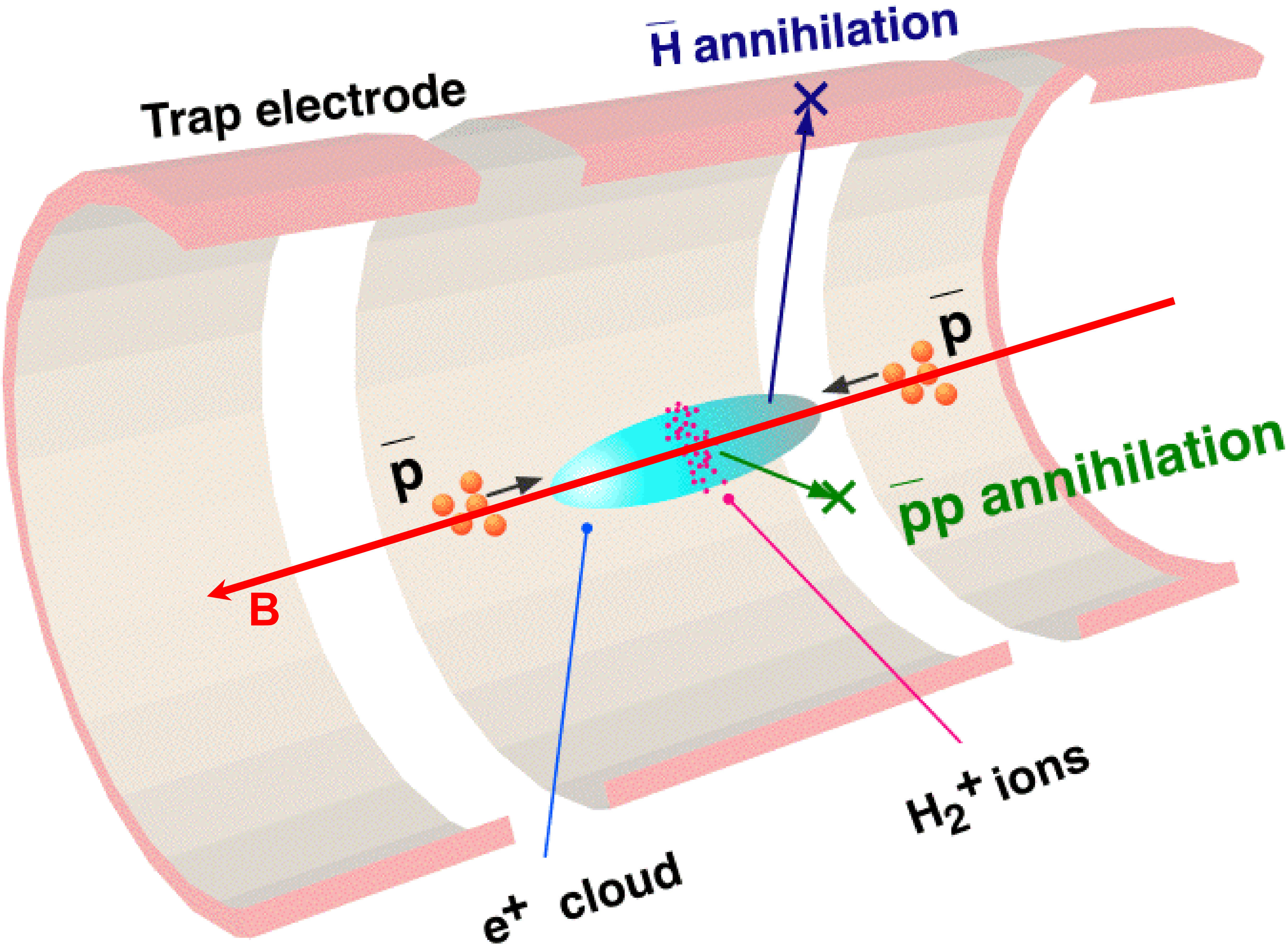


FIG. 3: Comparison of the axial distribution from cold mixing with a number of calculated distributions. Standard e^+ plasma parameters and $\mathbf{E} \times \mathbf{B}$ rotation were used except for the dot-dashed curve where $l_{e^+} = 60$ mm. Homogeneous formation in the plasma was assumed.


$\bar{H}$ annihilation
Trap electrode
$\bar{p}$
$\bar{p}$
B
$\bar{p}p$ annihilation
H_2^+ ions
e^+ cloud

ALPHA

Colaboração ALPHA

ALPHA

University of Aarhus, Denmark

Auburn University, USA

University of California Berkeley, USA

University of Calgary, Canada

University of Liverpool, U.K.

University of Manitoba, Canada

NRCN - Nucl. Res. Center Negev, Israel

RIKEN, Japan

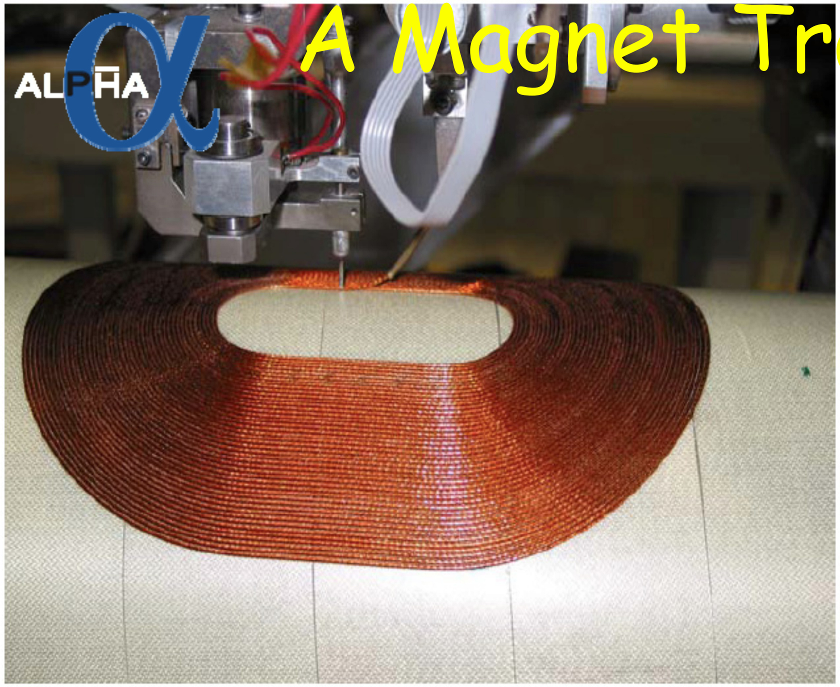
Federal University of Rio de Janeiro, Brazil

University of Wales Swansea, U.K.

University of Tokyo, Japan

TRIUMF, Canada

A Magnet Trap for AntiHydrogen



G. Andresen, et. al. (ALPHA Coll.) "Antimatter Plasmas in a Multipole Trap for Antihydrogen" Phys. Rev. Lett. 98, 023402 (2007)

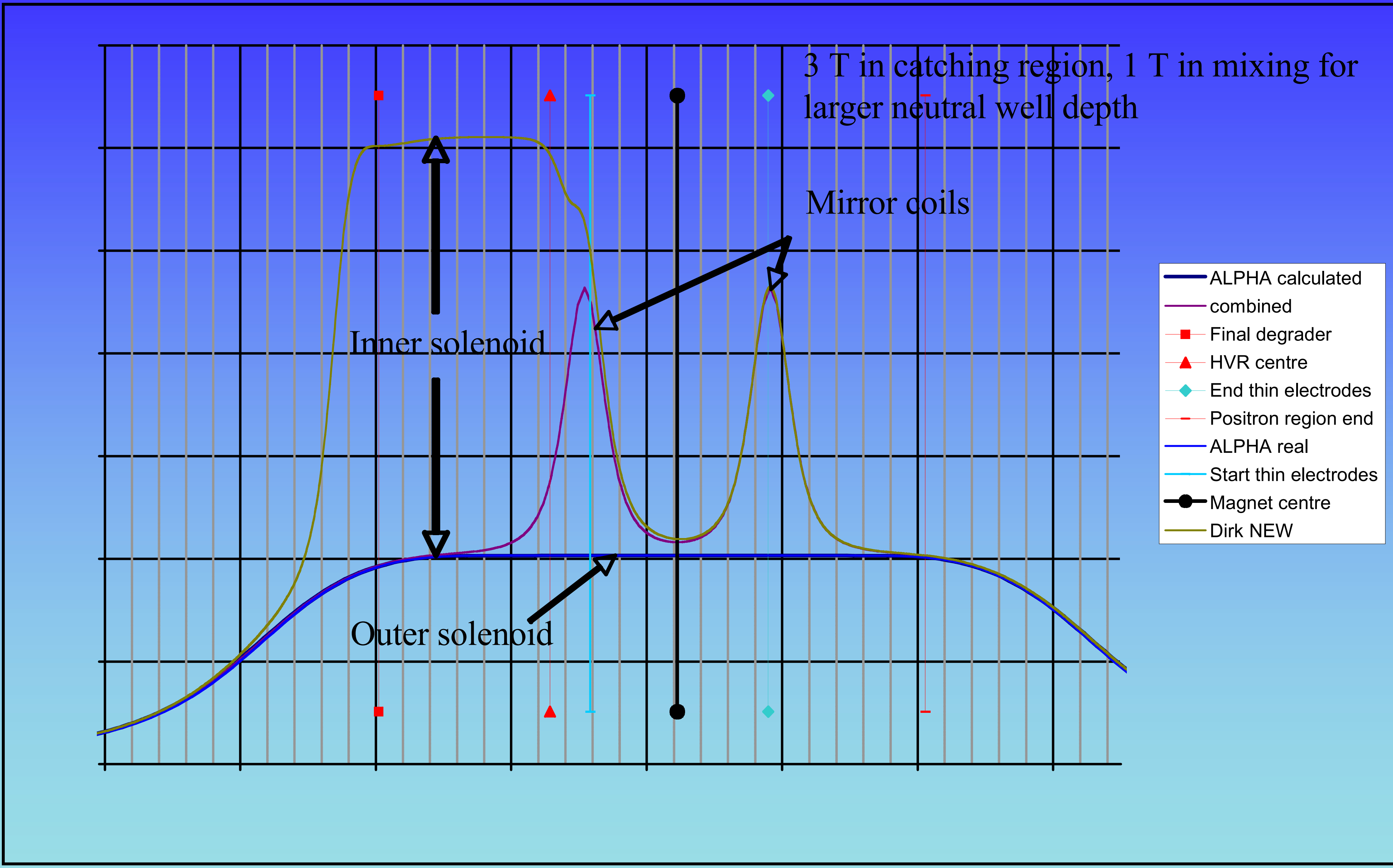
"Production of Antihydrogen at Reduced Magnetic Field for Anti-atom Trapping", Phys. Lett. B 41, 011001 (2008)

"Compression of antiproton clouds for antihydrogen trapping", Accepted, Phys. Rev. Lett. (2008)

Field Configuration - capturing pbars

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Field Configuration - trapping



A novel antiproton radial diagnostic based on octupole induced ballistic loss

G. B. Andresen,1 W. Bertsche,2 P. D. Bowe,1 C. C. Bray,3 E. Butler,2 C. L. Cesar,4
S. Chapman,3 M. Charlton,2 J. Fajans,3 M. C. Fujiwara,5 R. Funakoshi,6 D. R. Gill,5
J. S. Hangst,1 W. N. Hardy,7 R. S. Hayano,6 M. E. Hayden,8 A. J. Humphries,2
R. Hydomako,9 M. J. Jenkins,2 L. V. Jørgensen,2 L. Kurchaninov,5 R. Lambo,4 N. Madsen,2
P. Nolan,10 K. Olchanski,5 A. Olin,5 R. D. Page,10 A. Povilus,3 P. Pusa,10
F. Robicheaux,11 E. Sarid,12 S. Seif El Nasr,7 D. M. Silveira,4 J. W. Storey,5
R. I. Thompson,9 D. P. van der Werf,2 J. S. Wurtele,3 and Y. Yamazaki13

PHYSICS OF PLASMAS 15, 032107 2008

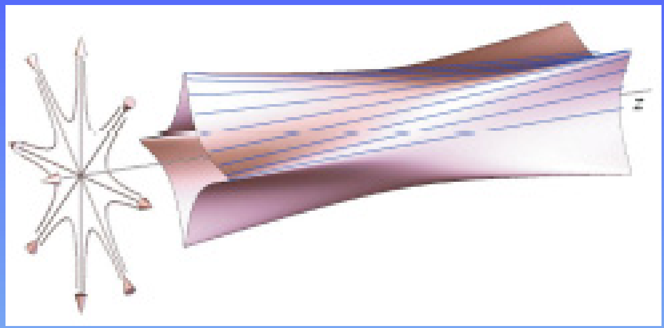
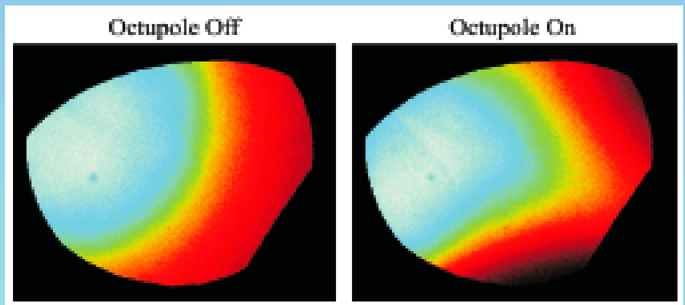
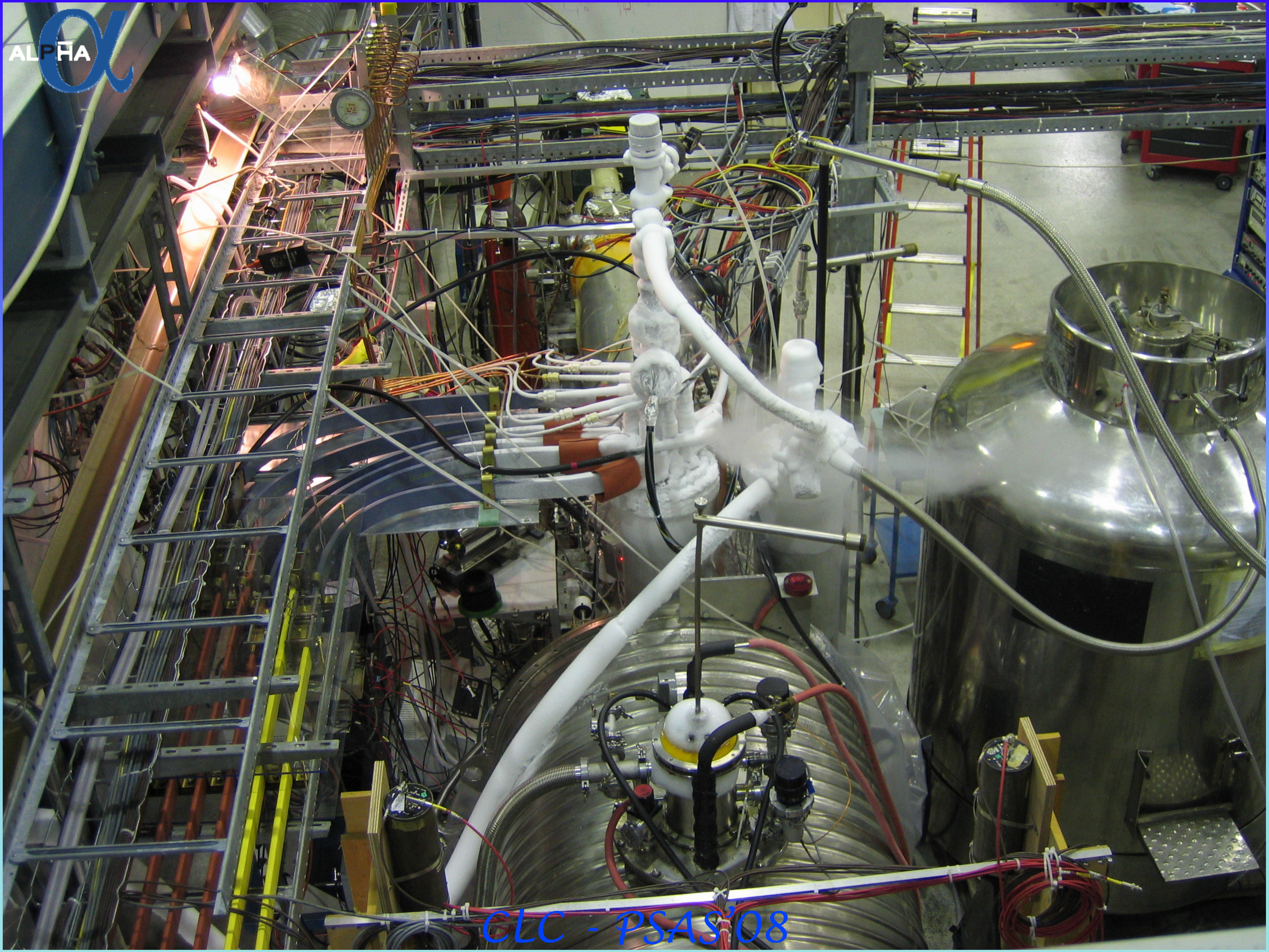


FIG. 2: Magnetic eld from the octupole and solenoid coils. The vectors on the left represent the directions of the axially-invariant eld from these coils. The surface is created by following the eld lines from a radially centered circular locus; the lines shown within the surface are eld lines.




ALPHA

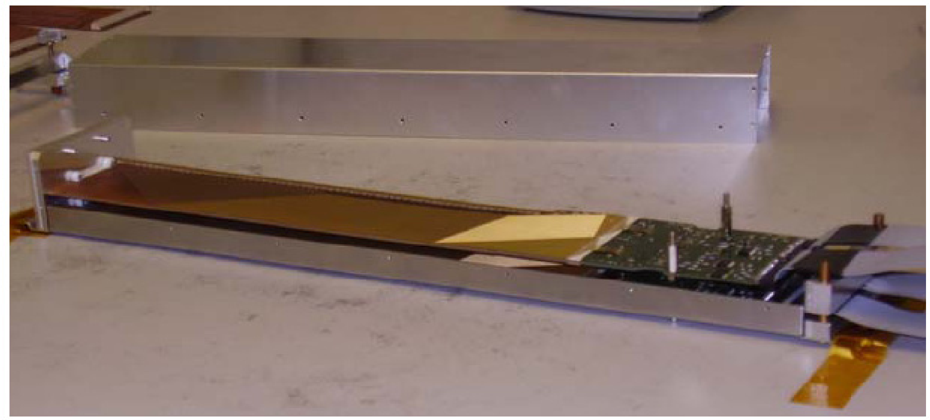
production of Hbar in trapping field

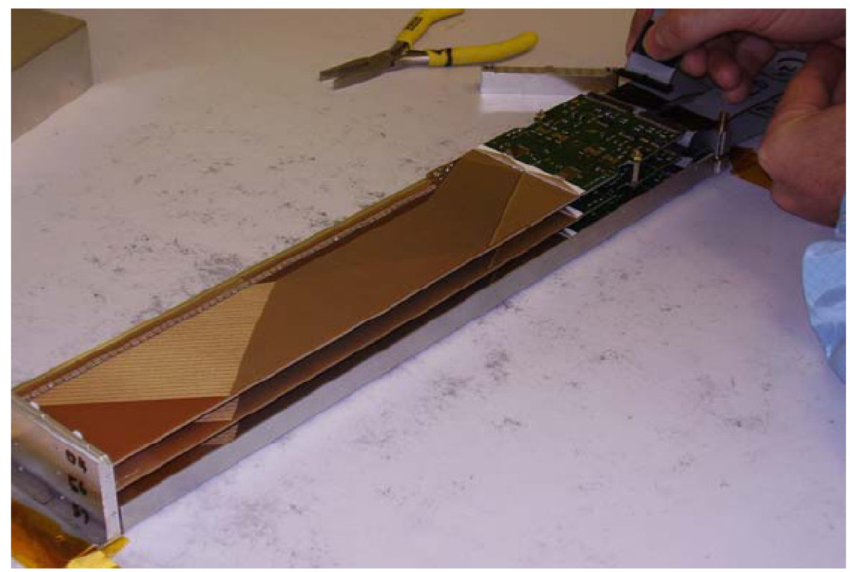
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

in 2008: detector

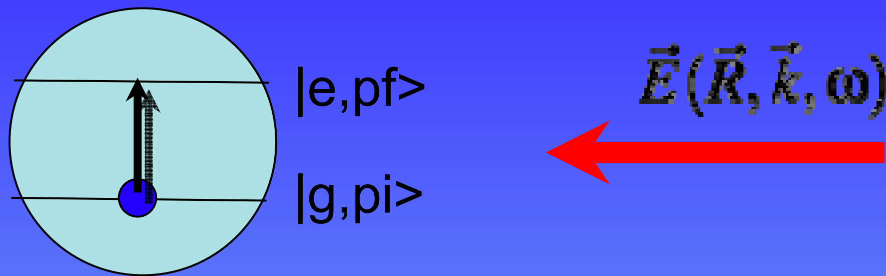
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



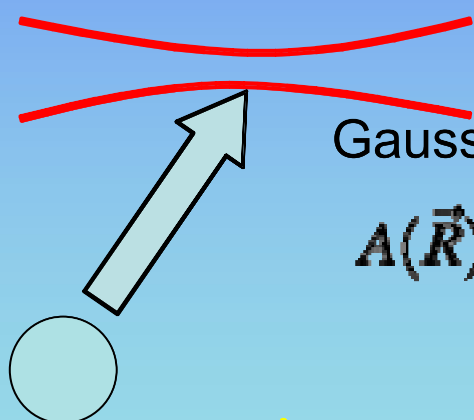


High-resolution Spectroscopy

$$w_{g\to e} \propto < e, \vec{p}_f | e\vec{r}\cdot\vec{E} | g, \vec{p}_i >$$
$$\propto \mu^j_{eg} < \vec{p}_f | e^{i\vec{k}\cdot\vec{R}} A(\vec{R}) | \vec{p}_i >$$
$$(onda\ plana) \Rightarrow \vec{k}_f = \vec{k}_i + \vec{k}$$
$$\frac{(\hbar k_f)^2}{2m} = \frac{(\hbar k_i)^2}{2m} + \frac{(\hbar)^2 \vec{k}\cdot\vec{k}_i}{m} + \frac{(\hbar k)^2}{2m}$$
$$K_f = K_i + \hbar\Delta\omega_{Doppler} + K_{recuo}$$
$$\Delta\omega_{Doppler} = \vec{k}\cdot\vec{v}$$



2-counterpropagating photons: Doppler-free



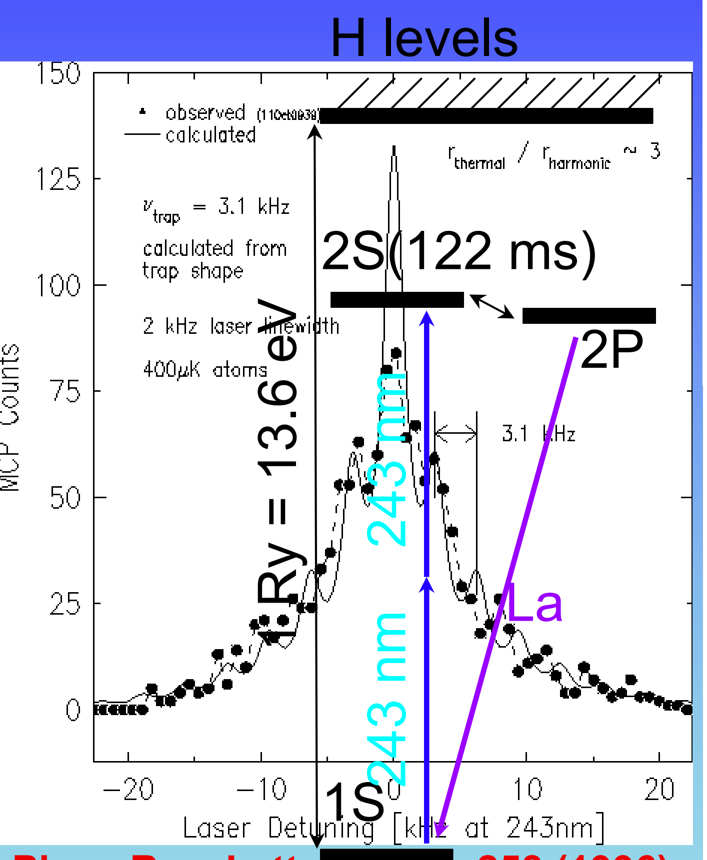
Gaussian Laser / 2 photons

$$A(\vec{R}) \propto e^{-(X^2+Y^2)/(2w^2(Z))} \Rightarrow$$

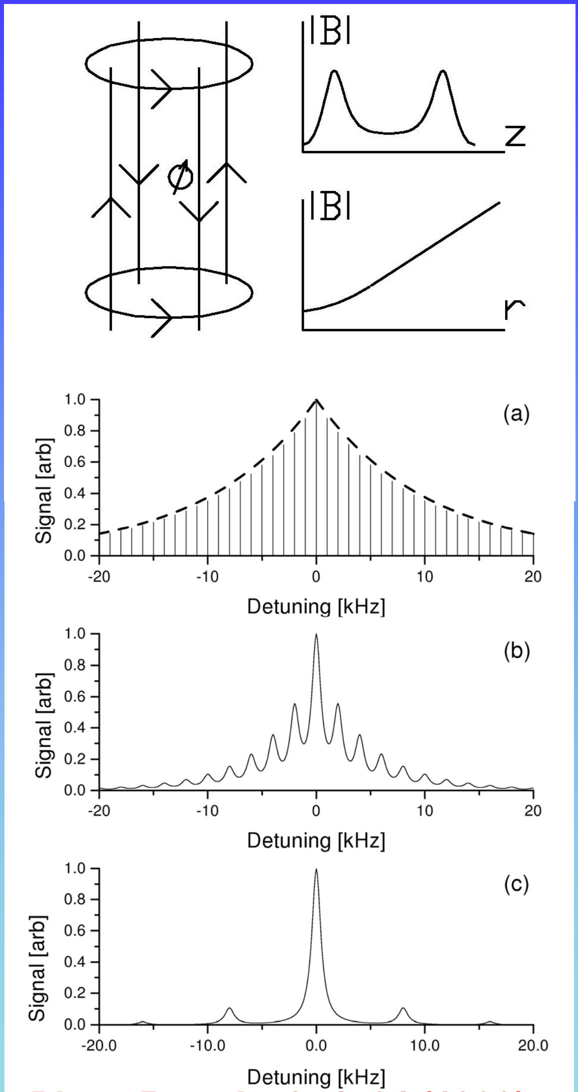
Time-of-Flight ~ Fourier Transform of the observation time ...
but ... with momenta exchange!
Also... 2nd-order Doppler Effect

ultra-cold atoms: minimize Relativistic 2nd. Doppler & Time-of-Flight

Spectroscopy Objectives
image e resemblance of H!?

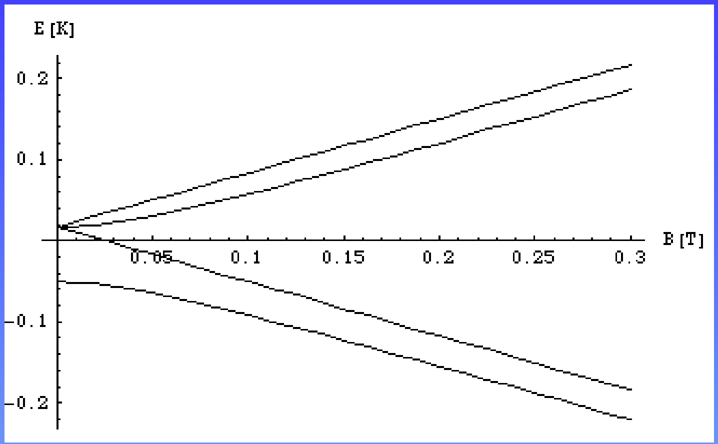


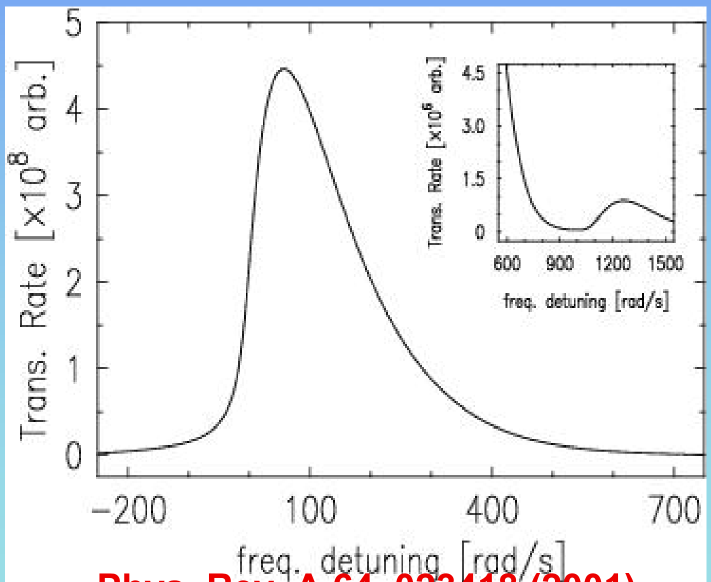
Phys. Rev. Lett. 77, 255–258 (1996)
Claudio L. Cesar et al.



Phys. Rev. A 59, 4564 (1999)

C. Cesar, D. Kleppner





Phys. Rev. A 64, 023418 (2001)
C. Cesar

CLC - PSAS'08

And ... talking about H trap:

- Trapping, Cooling
- Spectroscopy Hbar X H
- good H reference (?)
- lasers (?)

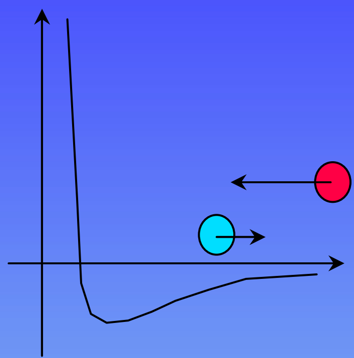
H trap (MIT) versus H beam (Hänsch & Biraben)

=== no more H trap in the world ===

Cooling atoms for trapping:

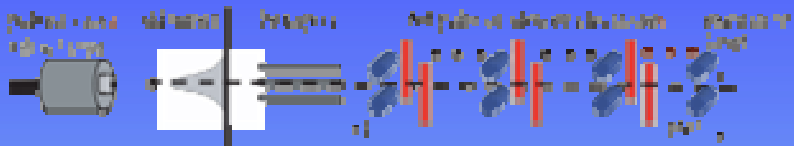
laser cooling:

H onto l-He



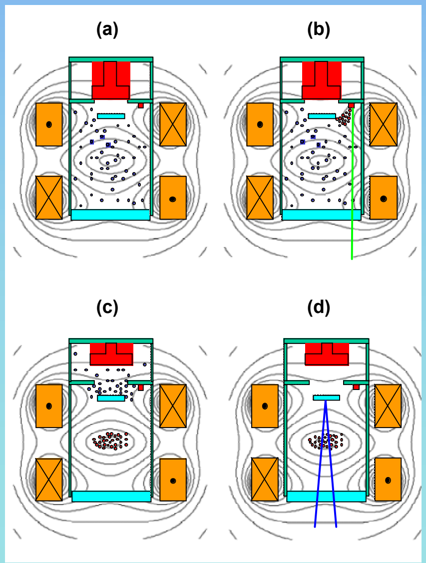
nobelprize.or
g

Stark Deceleration

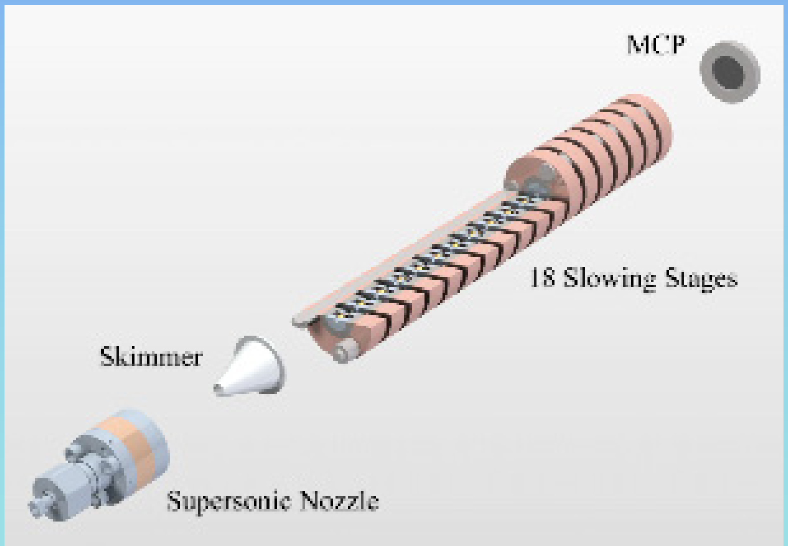


E.Hudson et al.

Doyle's buffer gas



M.Raizen's "coilgun"

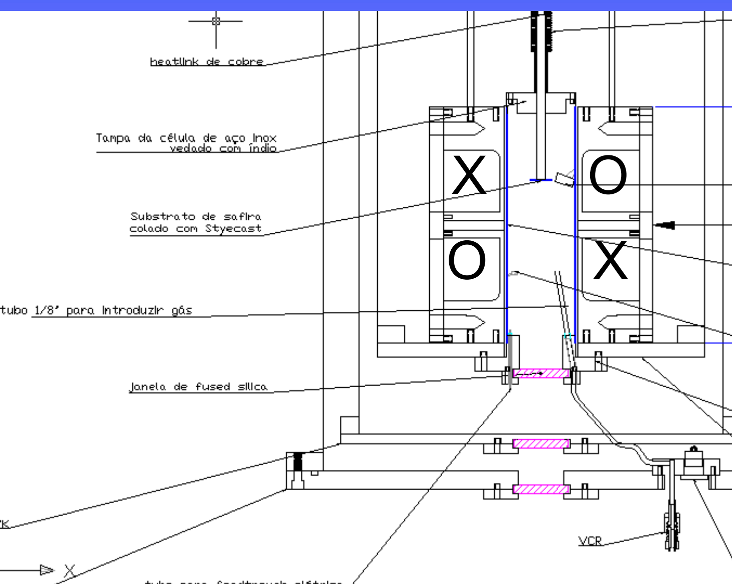


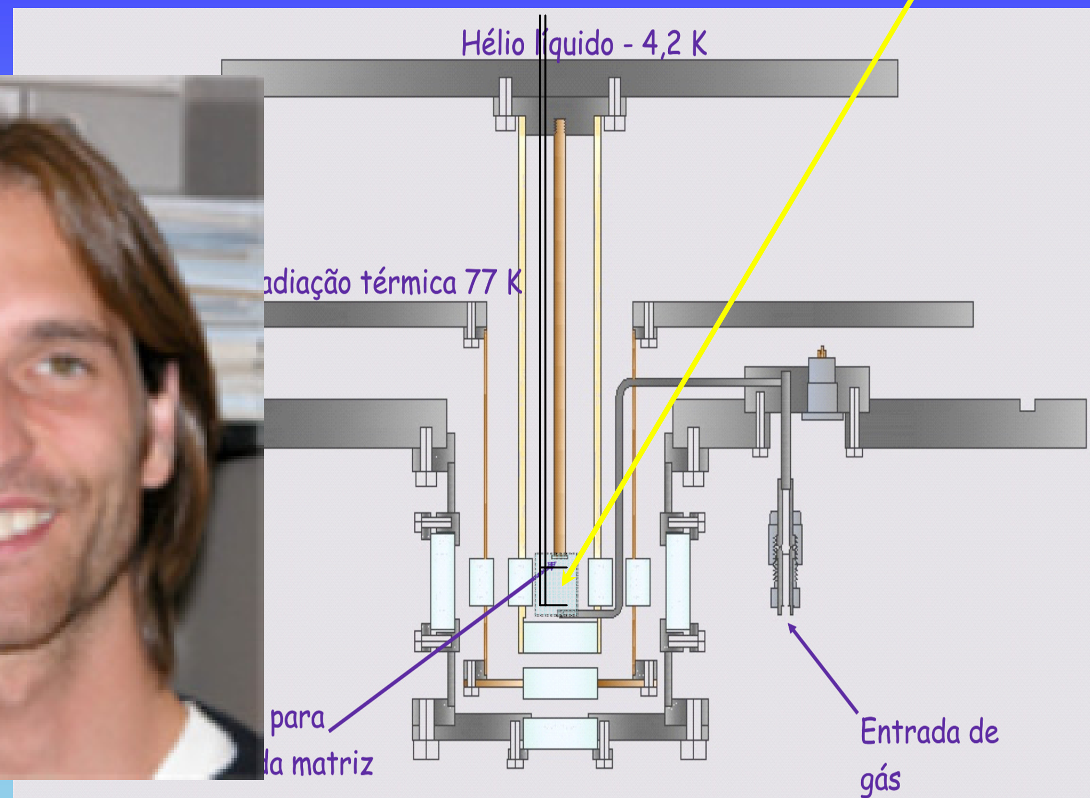
Raizen's "Paddle"

Two Projects: (See Paolo Crivelli's talk)

3 T high-L CW magnet

1 T miniature low-L switching magnet

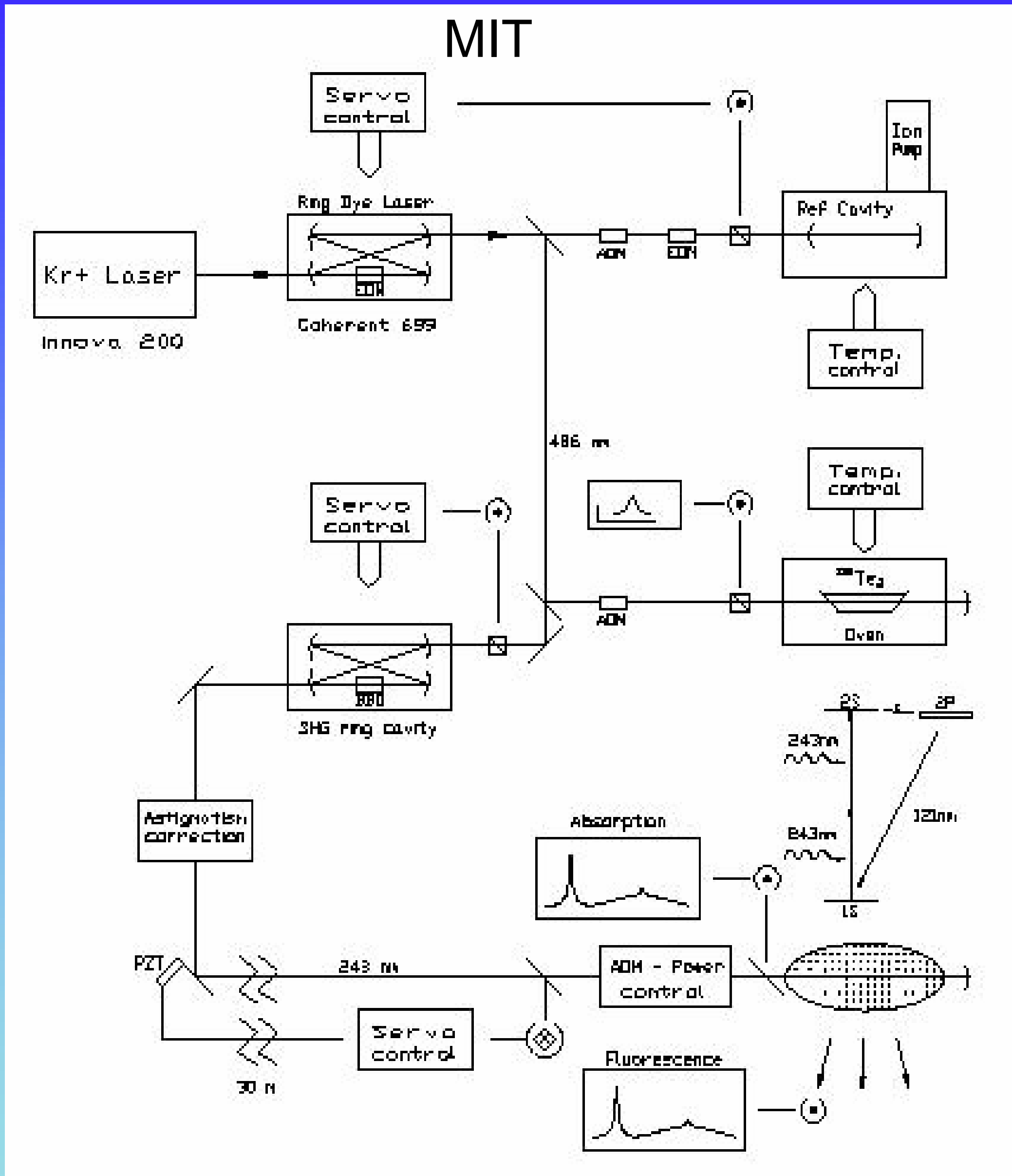


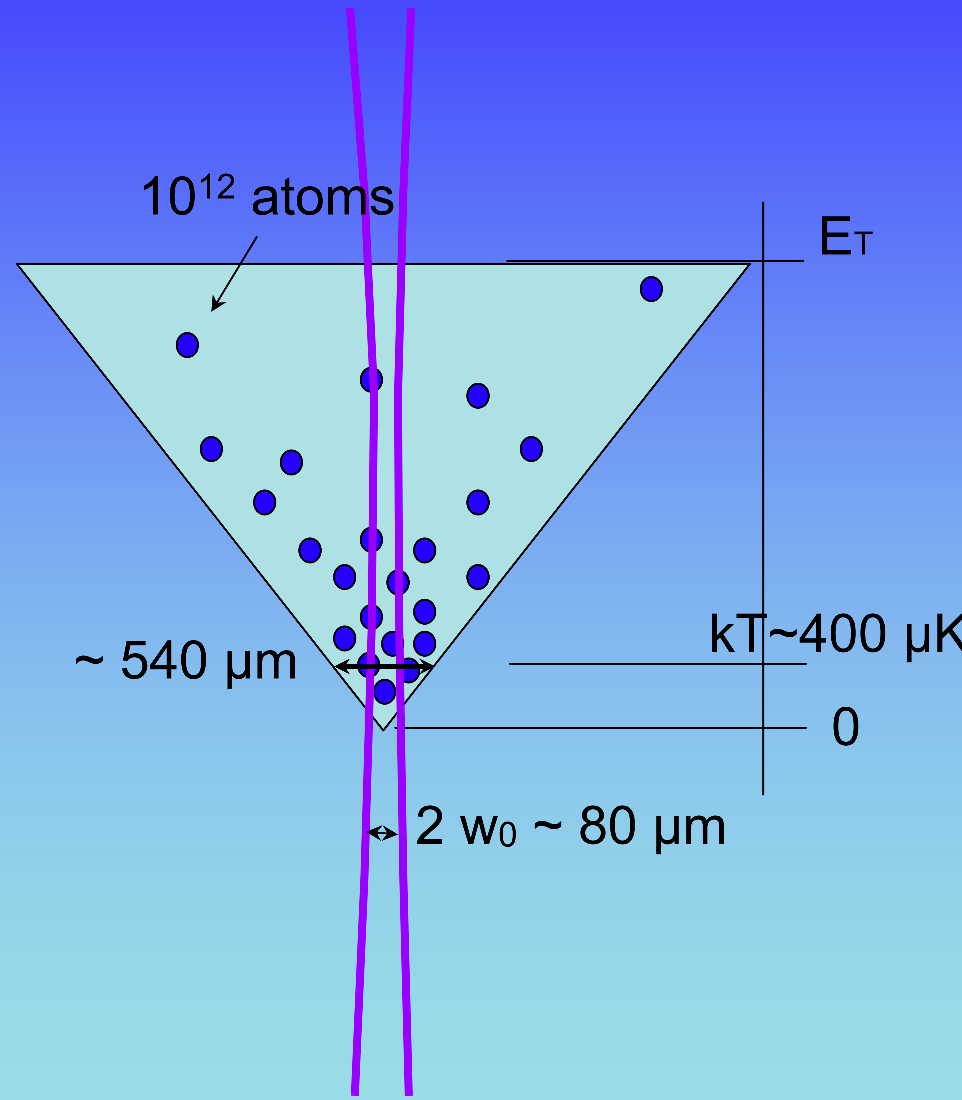


Aparato experimental para a co-deposição de um gás nobre e átomos de cromo ablacionados a laser

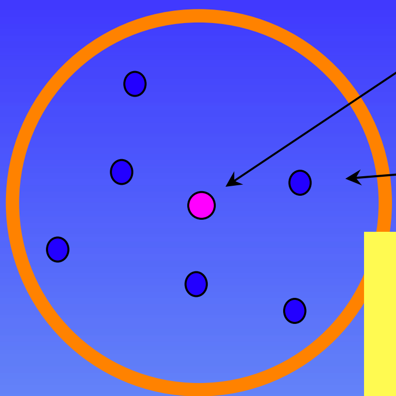
Prospects (?): 10^9 H+Li atoms @270 mK c/ 1 T

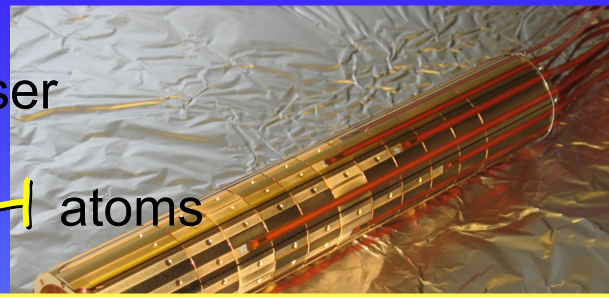
Towards a new Laser for H e H





Laser for H e H





Stable Diode

Amp

NbO_3

BBO

photons

$\Gamma_{exc}/\text{atom} =$

$(\gamma_{instr} \approx \gamma_{ti}$

$\propto \frac{p^2}{A^2}$

Useful numbers for thermal sample:

$$\delta\omega_{tof} = \frac{\sqrt{2kT/M}}{4\pi w(z)} \quad , \quad \delta\omega_Z \approx 10^6 M\ T$$

$$\delta\omega_{tof}(1K, w_0 = 10\mu m) \approx \delta\omega_Z(1K) \approx 10^6 rad/s$$

$$\delta\nu(1K) \approx 160M\ kHz \Rightarrow \frac{\delta\nu(1K)}{\nu} \approx \frac{1.3\times 10^{-10}}{f(S/N)}$$

$10^{-12} \Rightarrow$ would improve electron-positron mass comparison by 4 orders of magnitude

MIT Laser (10 n
in ALPHA:
- Geometric Overlap: ~ $4\text{x}10^{-6}$
- $Prob_{exc}$~10/s x 8 μs ~ $8\text{x}10^{-5}$ / atom.pass
- atom cross each ~ 0.25 s =>
need 3200 s ~ 1 h interaction for full excitation

goal: > 2 orders of magnitude

Proposal for microwave cooling of trapped antihydrogen

C. L. Cesar1 , F. Robicheaux2 and N. Zagury1

1

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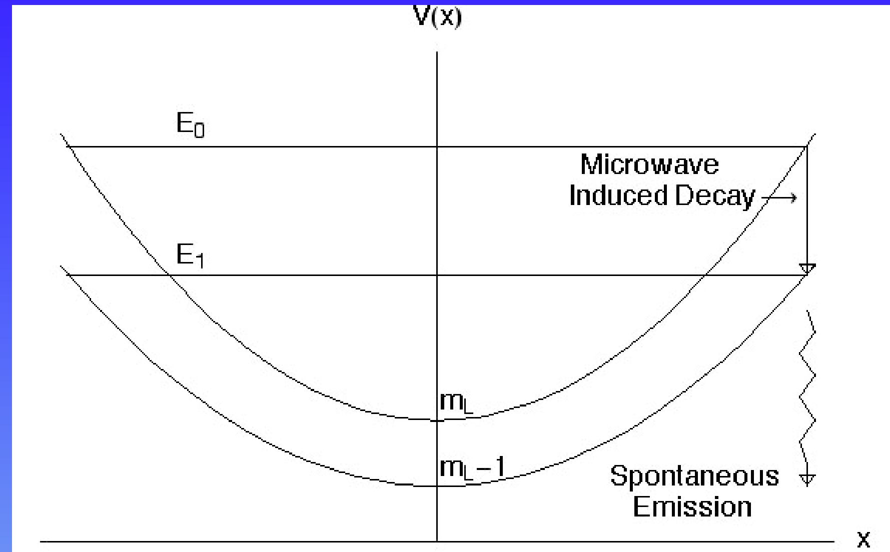
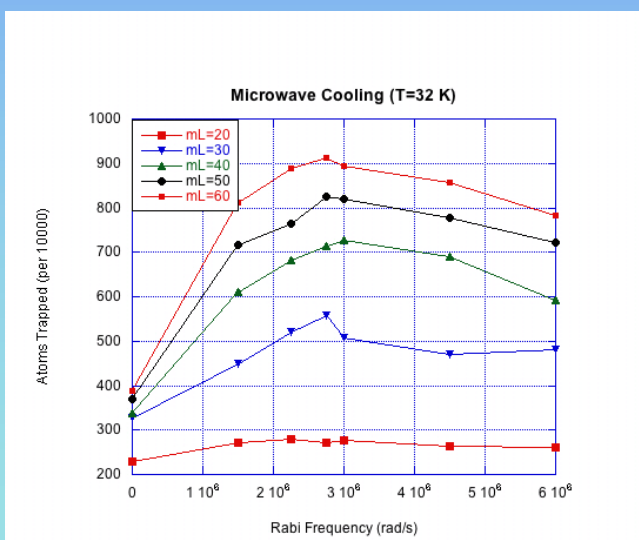
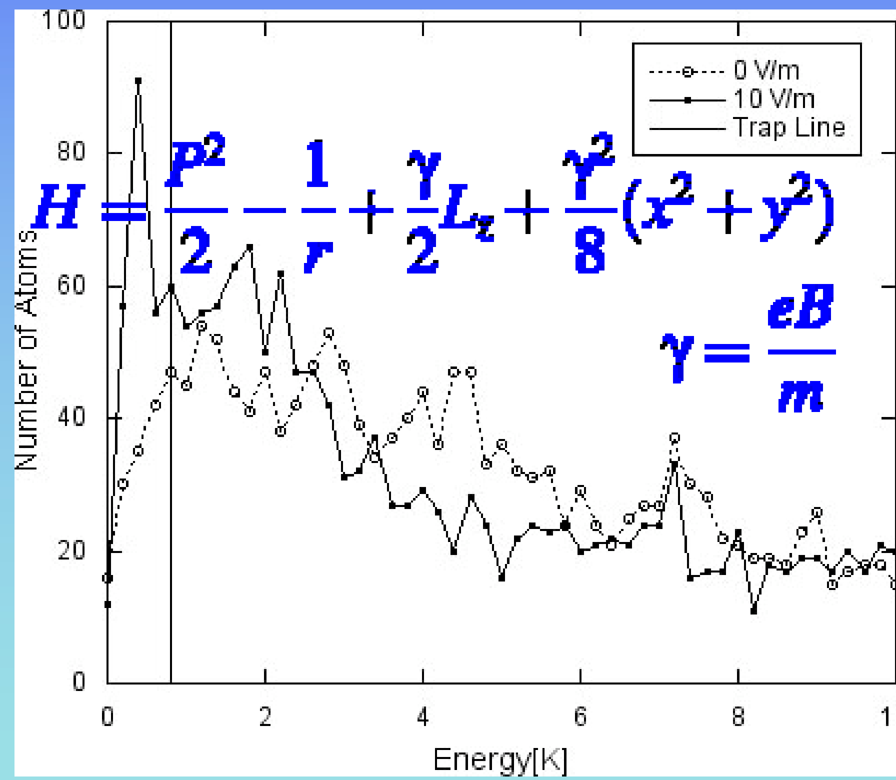
Abstract. We propose a usage of microwave radiation in a magnetic trap for improving the cooling and trapping of cold antihydrogen atoms which are initially produced at high magnetic moment states. Inducing transitions towards lower magnetic moments near the turning points of the atom in the trap, followed by spontaneous emission, should enhance the number of trappable atoms. We present results of simulations based on a typical experimental condition of the antihydrogen experiments at CERN. This technique should also be applicable to other trapped, high magnetic moment, Rydberg atoms.







$$H = \frac{P^2}{2} - \frac{1}{r} + \frac{\gamma}{2} L_z + \frac{\gamma^2}{8}(x^2 + y^2)$$

$$\gamma = \frac{eB}{m}$$

Conclusion and Perspectives

ATHENA

- **First cold antihidrogen atoms**
- **Positrons control, image techniques, beam, protonium formation!**

makers of fine and cool antihydrogen atoms since 2002

=> stay tunned!

ALPHA

- **New aparatus for magnetic trapping of antihydrogen (2008-?). After ... towards:**
- **μW Cooling, Spectroscopy (e^- e^+ mass comparison - huge improvement possible immediately)**
- **CPT testing, WEP testing (2010 -)**

RIO (see Paolo Crivelli's talk)

- **New trap for H, Li and light molecules**
- **New laser for H and antiH spectroscopy**

looking for students/pos-docs:

- cold atoms spectroscopy
- novel magnetic traps
- new laser for H and Hbar

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