MAX PLANCK INSTITUTE
FOR NUCLEAR PHYSICS

FLAIR, Liverpool, February 2011

“A New Route Towards Fundamental Tests with Anti-Hydrogen”

Based on a White Paper submitted to FLAIR (12/2009) by

Max-Planck-Institut
für Kernphysik

WHAT STARTS HERE CHANGES THE WORLD
THE UNIVERSITY OF TEXAS AT AUSTIN

Mark G. Raizen (UT, Austin)

and

Klaus Blaum (MPIK, Heidelberg)

MAX-PLANCK-GESELLSCHAFT

Outline

- Present situation with H-bar
- Open questions
- New techniques and developments
- Possible future applications

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Anti-Hydrogen

2002:
First production and detection of cold H-bar.

Gabrielse *et al.*, Phys. Rev. Lett. (2002)

Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States

G. Gabrielse,[1,*] N. S. Bowden,[1] P. Oxley,[1] A. Speck,[1] C. H. Storry,[1] J. N. Tan,[1] M. Wessels,[1] D. G. Schepers,[2] T. Sefzick,[2] J. Walz,[3] H. Pittner,[4] T.W. Hänsch,[4,5] and E. A. H

(ATRAP Collaboration)

Amoretti *et al.*, Nature (2002)

advance online publication

Production and detection of cold antihydrogen atoms

M. Amoretti[*], C. Amsler[†], G. Bonomi[‡§], A. Bouchta[‡], P. Bowe[||], C. Carraro[*], C. L. Cesar[¶], M. Charlton[#], M. J. T. Collier[#], M. Doser[‡], V. Filippini[☆], K. S. Fine[‡], A. Fontana[☆**], M. C. Fujiwara[††], R. Funakoshi[††], P. Genova[☆**], J. S. Hangst[||], R. S. Hayano[††], M. H. Holzscheiter[‡], L. V. Jørgensen[#], V. Lagomarsino[*‡‡], R. Landua[‡], D. Lindelöf[†], E. Lodi Rizzini[§☆], M. Macrì[*], N. Madsen[†], G. Manuzio[*‡‡], M. Marchesotti[☆], P. Montagna[☆**], H. Pruys[†], C. Regenfus[†], P. Riedler[‡], J. Rochet[†#], A. Rotondi[☆**], G. Rouleau[†#], G. Testera[*], A. Variola[*],

LETTER

2010/2011:
First trapped H-bar. (38 events)

Trapped antihydrogen

G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], S. Chapman[3], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], J. S. Hangst[1], W. N. Hardy[9], M. E. Hayden[2], A. J. Humphries[4], R. Hydomako[7], M. J. Jenkins[4], S. Jonsell[10], L. V. Jørgensen[4], L. Kurchaninov[8], N. Madsen[4], S. Menary[11], P. Nolan[12], K. Olchanski[8], A. Olin[8], A. Povilus[3], P. Pusa[12], F. Robicheaux[13], E. Sarid[14], S. Seif el Nasr[9], D. M. Silveira[15], C. So[3], J. W. Storey[8]†, R. I. Thompson[7], D. P. van der Werf[4], J. S. Wurtele[3,6] & Y. Yamazaki[15,16]

“One of the problems with the current approach is that the anti-hydrogen atoms must be trapped *in-situ*.“

A new route

Our approach is to first build an off-line mirror experiment with matter, as a testing ground for our methods.

New approaches to trapping and cooling of charged particles (Blaum) with general methods of trapping and cooling of neutral atoms (Raizen)

The basic strategy of the mirror system is to trap and cool protons and electrons in a cryogenic Penning trap. The protons will then be launched to form a beam of neutral hydrogen atoms, which will be stopped and cooled.

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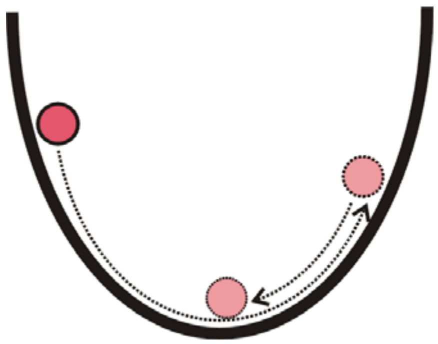
Cooling of trapped particles

Cooling



Manipulation of ion motion

Dissipation of energy

Escape of hottest particles

- ➢ increase of luminosity
- ➢ small amplitudes
- ➢ q/m-separation
- ➢ emittance improvement
- ➢ Doppler width reduction

Cooling techniques

	Type of cooling applied to		
	Ion trap	Stor. ring	Atom trap
laser cooling	✓✓	✓	✓✓
buffer gas cooling	✓✓		
electron cooling	✓	✓✓	
stochastic cooling		✓✓	
evaporative cooling	✓		✓
sympathetic cooling	✓		✓
resistive cooling	✓✓		

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Laser cooling

Laser cooling and trapping

Nobel Prize 1997

Stringent Requirements:

2-level cycling transition

Transition accessible with lasers

What about hydrogen? → J. Walz

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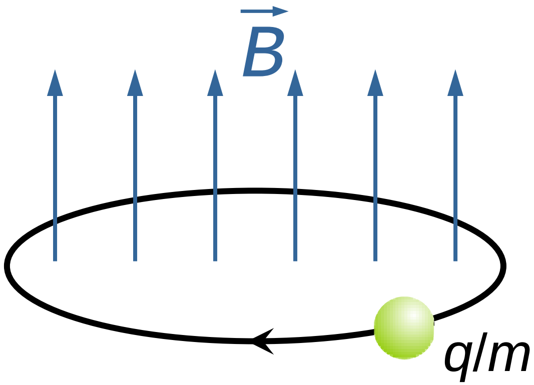
Principle of Penning traps

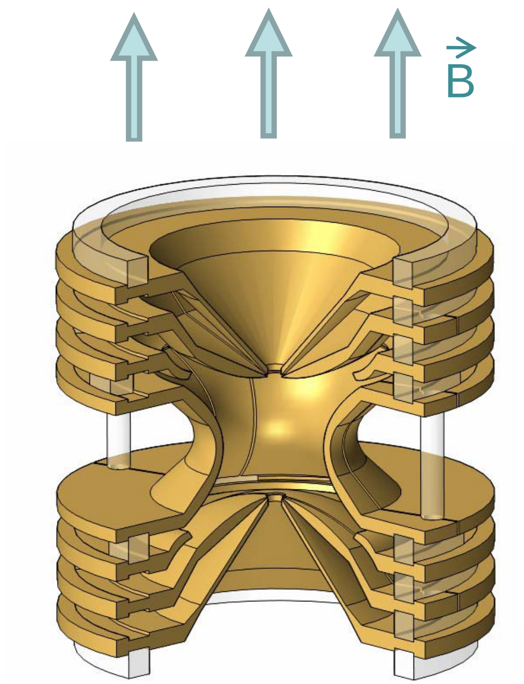


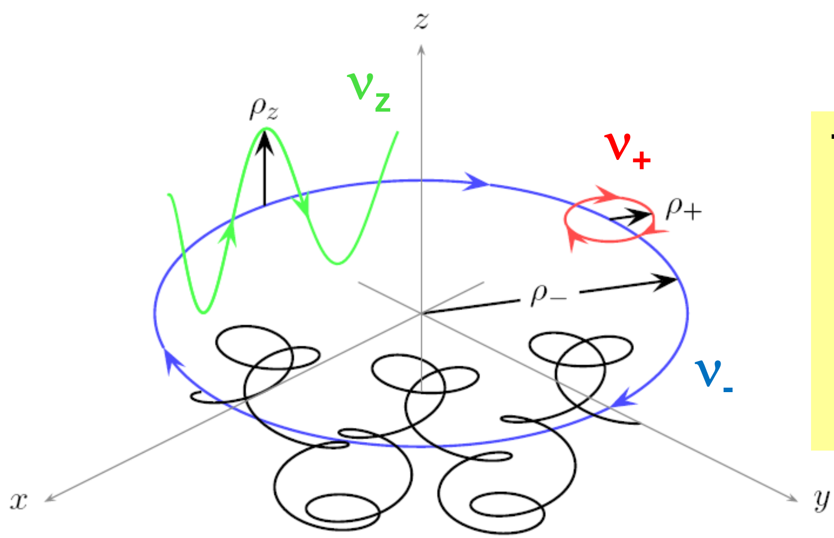
Cyclotron frequency:

$$f_c = \frac{1}{2\pi}\cdot\frac{q}{m}\cdot B$$

PENNING trap

- Strong homogen. magnetic field
- Weak electric 3D quadrupole field





Typical freq.
q = e
m = 1 u
B = 6 T
$f_c \approx$ 100 MHz

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Tasks to charged particle storage

- Storage of a large number of protons and electrons ⇨ **10^8**
- Sensitive non-destructive detection ⇨ **1**
- Fast cooling of the charged particles ⇨ **ms-s**
- Efficient cooling of antiprotons ⇨ **???**

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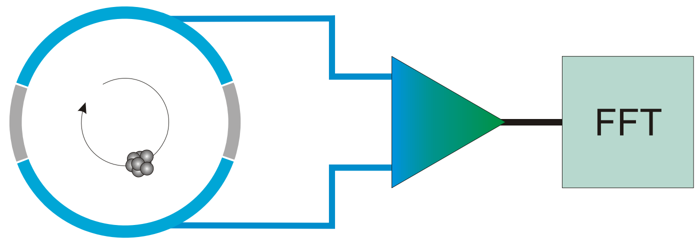
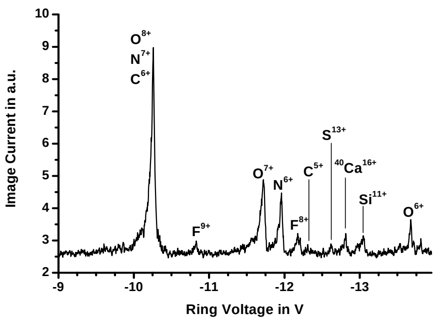
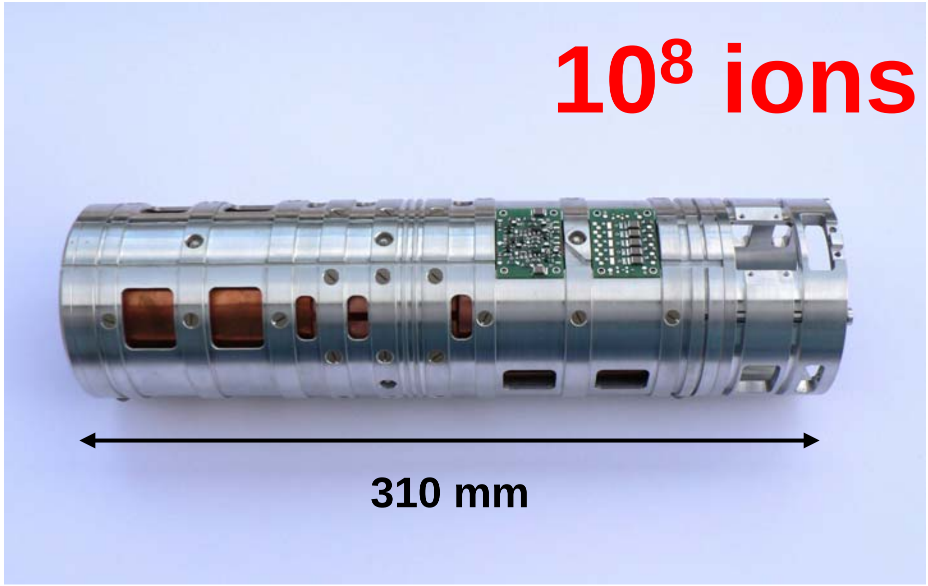
Storage of a large number of ions

Penning traps as high-precision “rest-gas analyser“

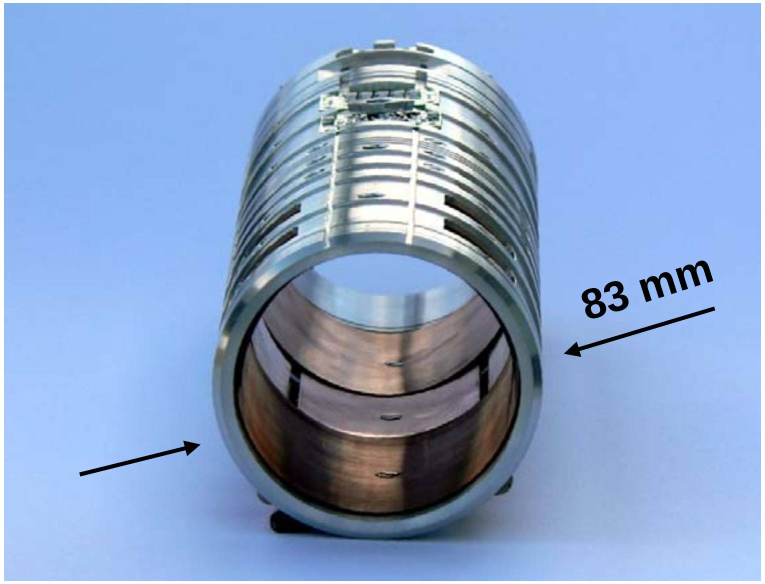
Broad-band
FT-ICR
kHz-MHz







KATRIN-TRAP



M. Ubieto Díaz *et al*., Int. J. Mass Spectrom. 288, 1 (2009)

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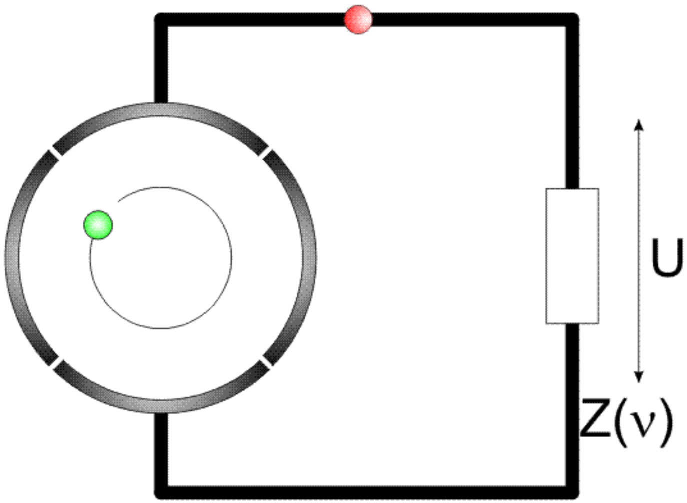
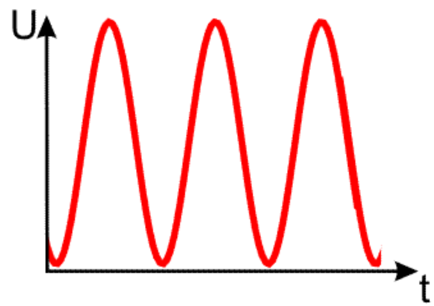
Non-destructive ion detection



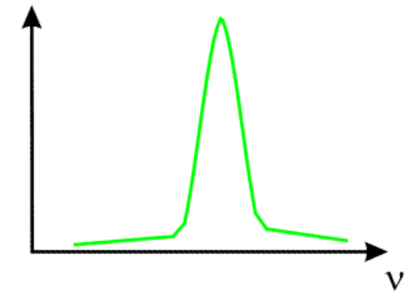
ion signal



very small signal ~fA

mass/frequency spectrum

Amplitude



„FT-ICR“

Fourier-**T**ransform-
Ion **C**yclotron **R**esonance

Operation of traps and electronics at **cryogenic** (4 K) temperature.

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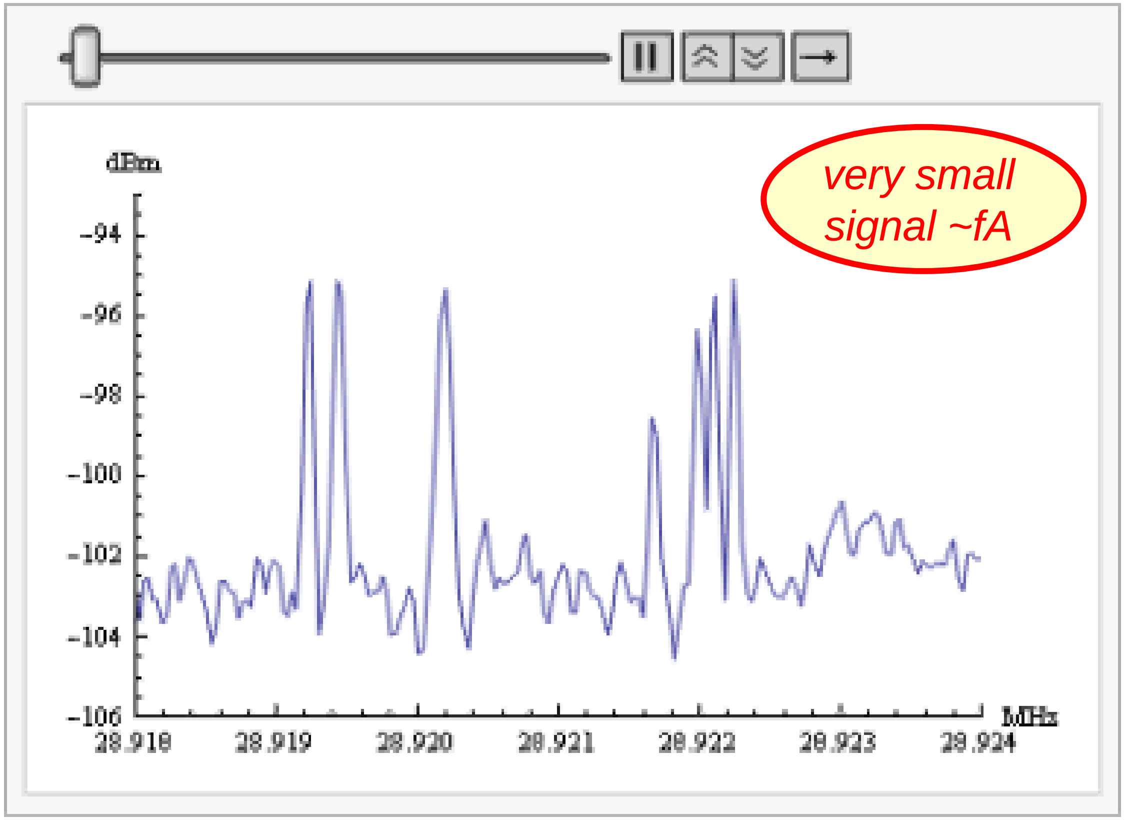
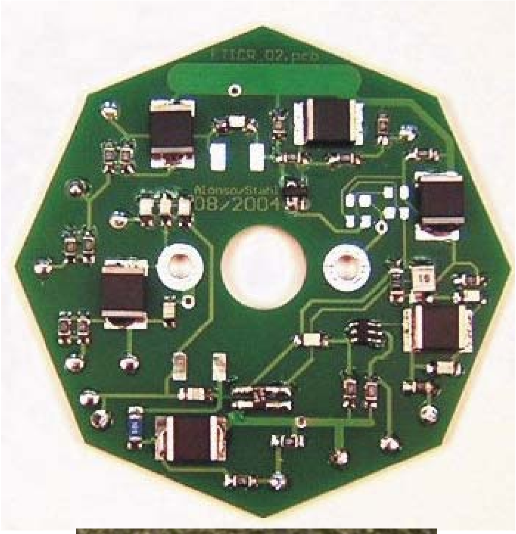
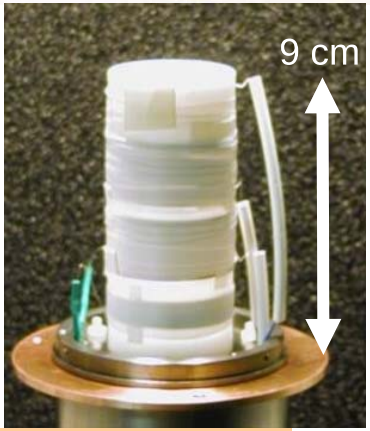
Resistive /evaporative cooling



complex electronics





Direct evaporative cooling of anti-protons is not viable, since it would lead to a huge loss in number.

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Evaporative / Adiabatic cooling

PRL **105,** 013003 (2010) PHYSICAL REVIEW LETTERS week ending 2 JULY 2010

Evaporative Cooling of Antiprotons to Cryogenic Temperatures

G. B. Andresen,[1] M. D. Ashkezari,[2] M. Baquero-Ruiz,[3] W. Bertsche,[4] P. D. Bowe,[1] E. Butler,[4] C. L. Cesar,[5] S. Chapman,[3] M. Charlton,[4] J. Fajans,[3] T. Friesen,[6] M. C. Fujiwara,[7] D. R. Gill,[7] J. S. Hangst,[1] W. N. Hardy,[8] R. S. Hayano,[9] M. E. Hayden,[2] A. Humphries,[4] R. Hydomako,[6] S. Jonsell,[4,10] L. Kurchaninov,[7] R. Lambo,[5] N. Madsen,[4] S. Menary,[11] P. Nolan,[12] K. Olchanski,[7] A. Olin,[7] A. Povilus,[3] P. Pusa,[12] F. Robicheaux,[13] E. Sarid,[14] D. M. Silveira,[15,16] C. So,[3] J. W. Storey,[7] R. I. Thompson,[6] D. P. van der Werf,[4] D. Wilding,[4] J. S. Wurtele,[3] and Y. Yamazaki[15,16]

(ALPHA Collaboration)

PRL **106,** 073002 (2011) PHYSICAL REVIEW LETTERS week ending 18 FEBRUARY 2011

Adiabatic Cooling of Antiprotons

G. Gabrielse,[1,*] W. S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] R. Kalra,[1] E. Novitski,[1] D. Grzonka,[2] W. Oelert,[1] T. Sefzick,[2] M. Zielinski,[2] D. Fitzakerley,[3] M. C. George,[3] E. A. Hessels,[3] C. H. Storry,[3] M. Weel,[3] A. Müllers,[4] and J. Walz[4]

(ATRAP Collaboration)

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[2]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[3]*Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada*
[4]*Institut für Physik, Johannes Gutenberg Universität and Helmholtz Institut Mainz, D-55099 Mainz, Germany*
(Received 1 December 2010; published 15 February 2011)

Adiabatic cooling is shown to be a simple and effective method to cool many charged particles in a trap to very low temperatures. Up to 3×10^6 $\bar{p}$ are cooled to 3.5 K—10^3 times more cold $\bar{p}$ and a 3 times lower

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Laser cooling of negative ions

PRL **102,** 043001 (2009) PHYSICAL REVIEW LETTERS week ending 30 JANUARY 2009

High-Resolution Laser Spectroscopy on the Negative Osmium Ion

U. Warring,* M. Amoretti, C. Canali, A. Fischer, R. Heyne, J. O. Meier, Ch. Morhard, and A. Kellerbauer†

Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany

(Received 5 October 2008; published 30 January 2009)

We have applied a combination of laser excitation and electric-field detachment to negative atomic ions for the first time, resulting in an enhancement of the excited-state detection efficiency for spectroscopy by at least 2 orders of magnitude. Applying the new method, a measurement of the bound-bound electric-

Direct laser cooling of negative ions is not promising.

REVIEW OF SCIENTIFIC INSTRUMENTS **81**, 013301 (2010)

Production of negative osmium ions by laser desorption and ionization

D. Rodríguez,[1,a)] V. Sonnenschein,[2,b)] K. Blaum,[3,4] M. Block,[5] H.-J. Kluge,[4,5]
A. M. Lallena,[1] S. Raeder,[2] and K. Wendt[2]

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[2]*Institut für Physik, Johannes Gutenberg-Universität, 55099 Mainz, Germany*
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[5]*GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*

Tasks to neutral particle storage

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- Deceleration and stopping of a neutral particle beam ⇨ **done**
- Cooling of neutral H atoms ⇨ **soon**
- Detection of stored H atoms ⇨ **in prog.**
- Precision experiments ⇨ **???**

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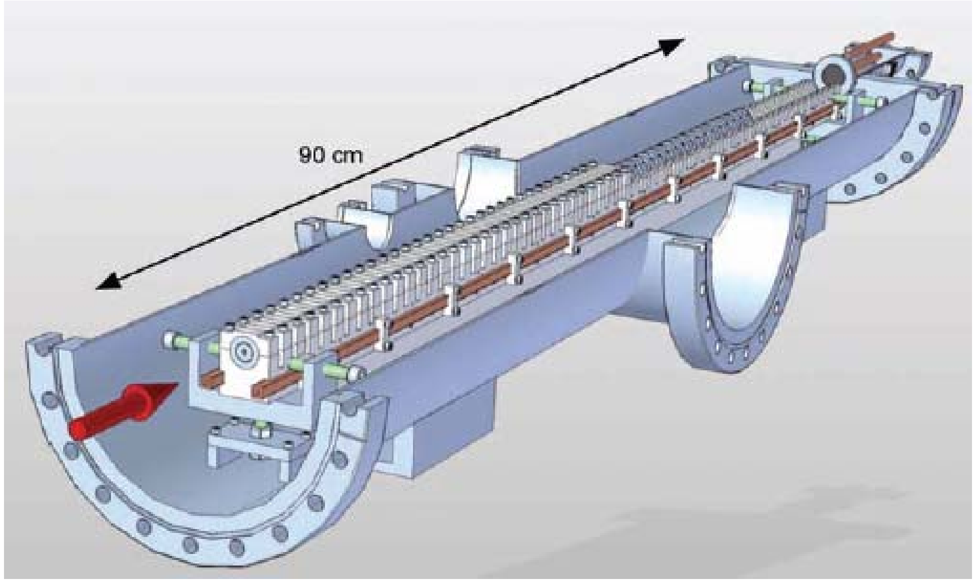
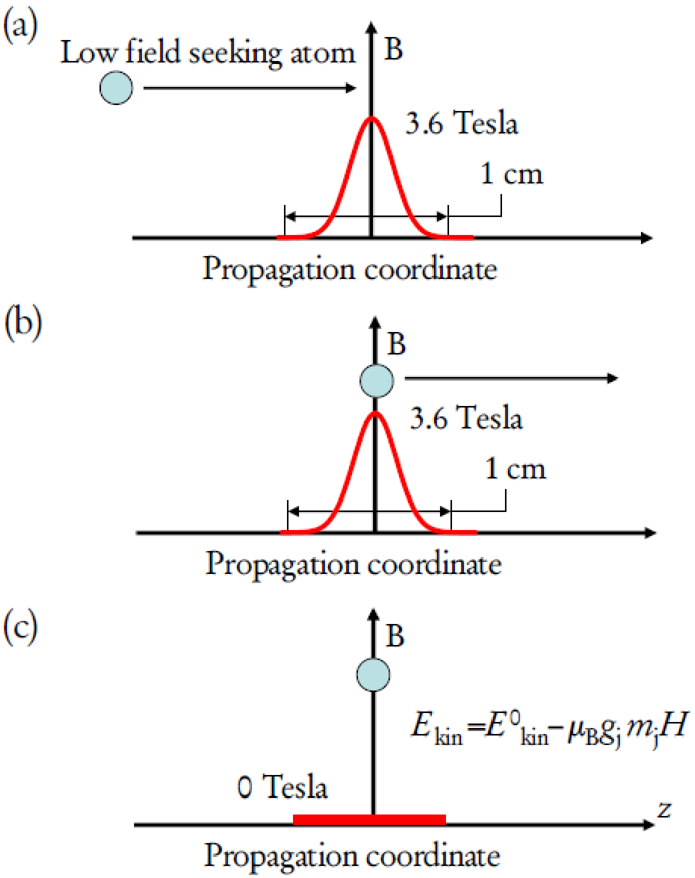
Atomic coilgun

- Directly slow and stop a beam of paramagnetic atoms





Analogy to Stark Decelerator:
F. Merkt (Zürch), G. Meijers (Berlin)

Efficiency: 2-10%   Temperature: 80 mK

Most atoms in periodic table elements are paramagnetic

E. Narevicius *et al*., Phys. Rev. Lett. 100, 093003 (2008)

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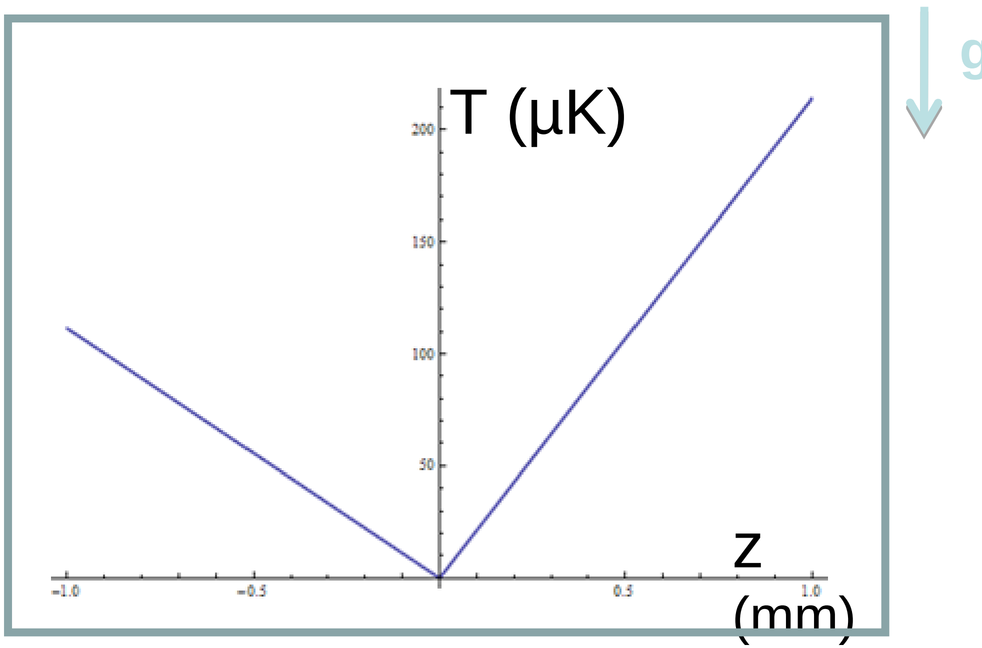
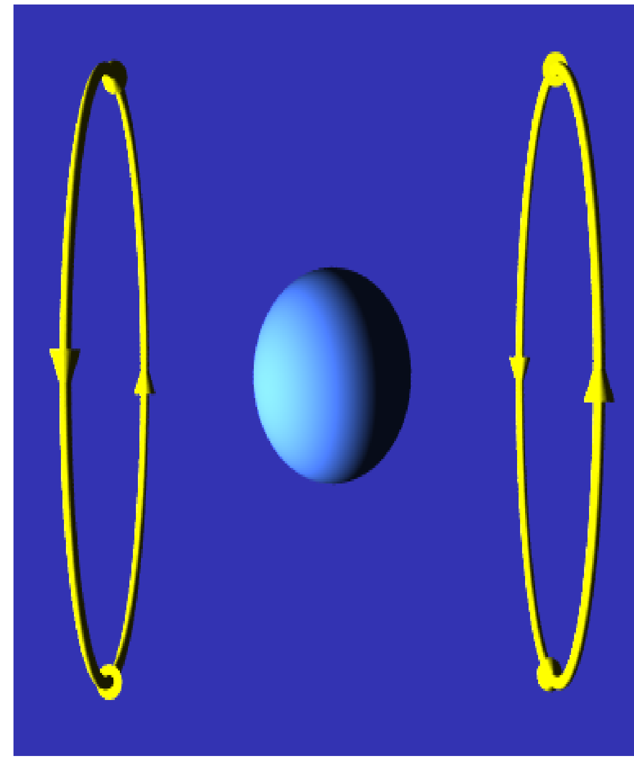
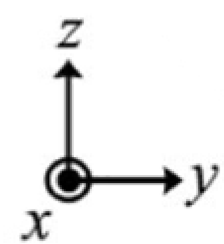
Atom Trapping

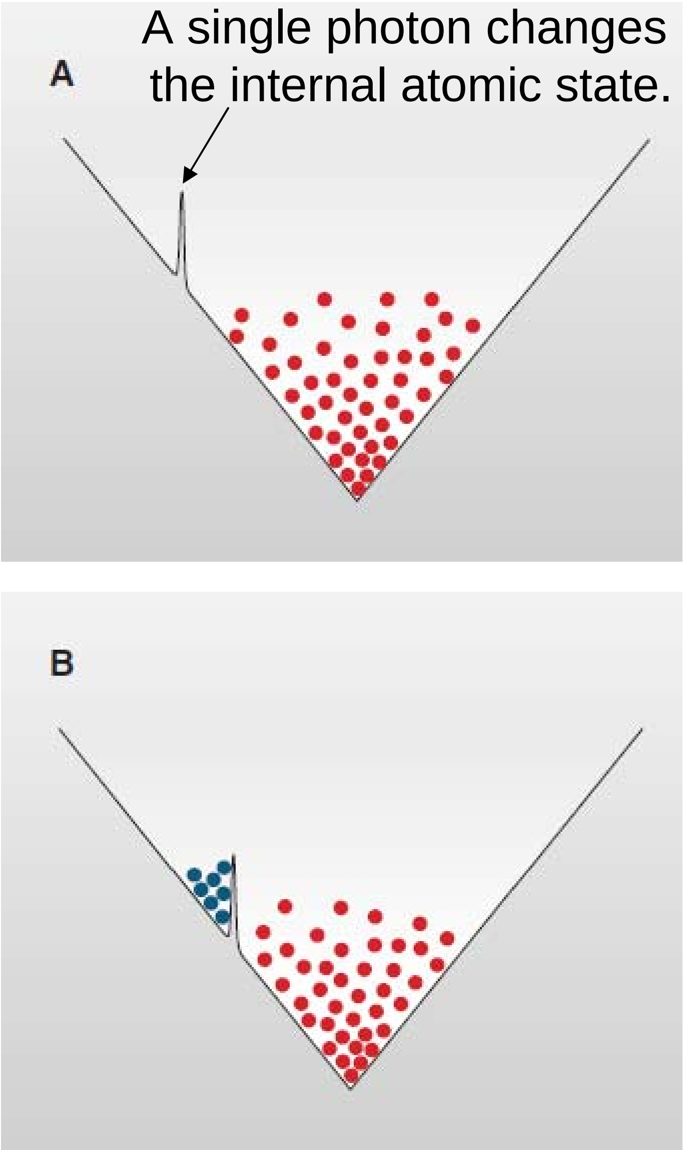


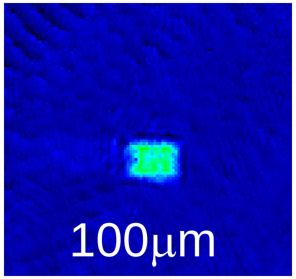




$$E = \mu_B \, |B| + mgz$$

Single-photon atomic cooling





T ~ a few mK

350x increase in phase space density from magnetic trap!

G. Price et al., Phys. Rev. Lett. 100, 093003 (2008)

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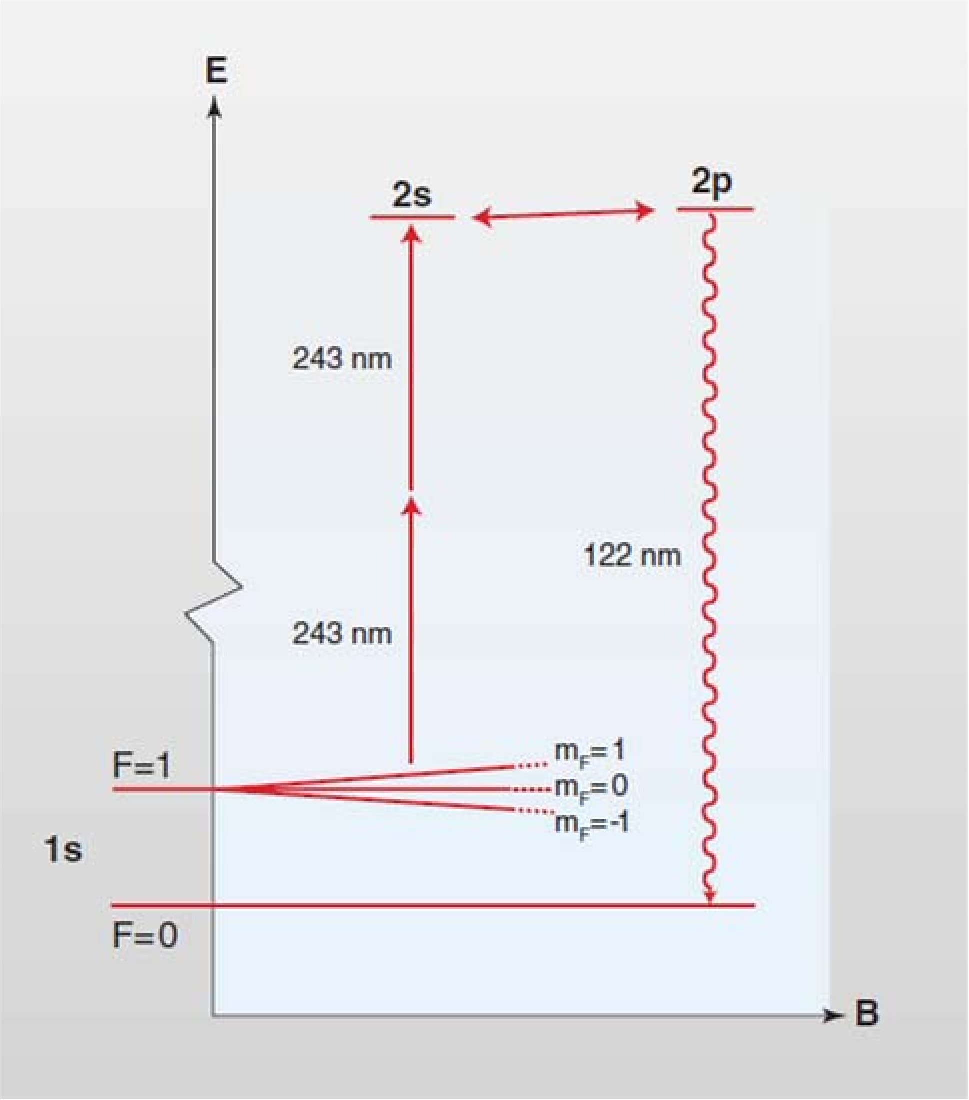
Laser scheme for single-photon cooling



1) Diode laser with tapered amplifier at λ = 972 nm.
2) Frequency doubling in a resonant build-up cavity to λ = 486 nm. (Coherent MPD)
3) Frequency doubling in a resonant build-up cavity to λ = 243 nm. (Coherent MPD)
   → 5 mW output power.
4) Confocal build-up cavity around the atoms.
   → 100x power increase.

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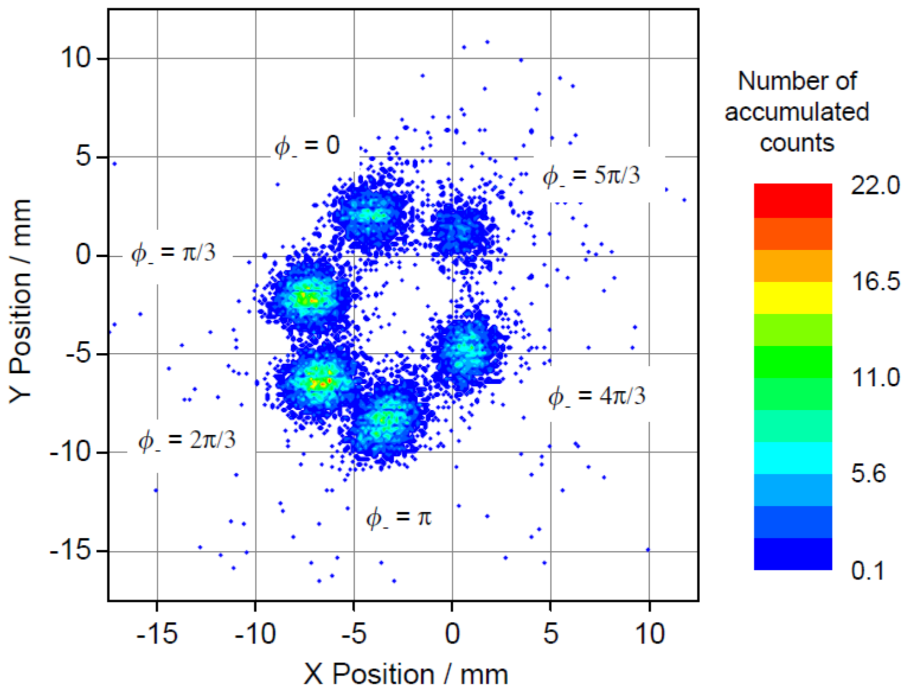
Detection of neutral stored H

1. Drive a transition to the 2S state in the *m*=1 state.
2. Launch the atoms magnetically with a coil.
3. Detection with a neutral particle detector.



Space resolving MCP detector.

G. Eitel et al., NIMA, 606, 475 (2009)

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Summary

Our approach is to first build an off-line mirror experiment with matter, as a testing ground for our methods.

Four-step solution

1. **Storage of a large number of p and e, form H beam**
2. **Atomic coilgun for deceleration and stopping of H**
3. **Single-photon cooling**
4. **Neutral H detection**

This is a totally new approach to produce cold H-bar

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