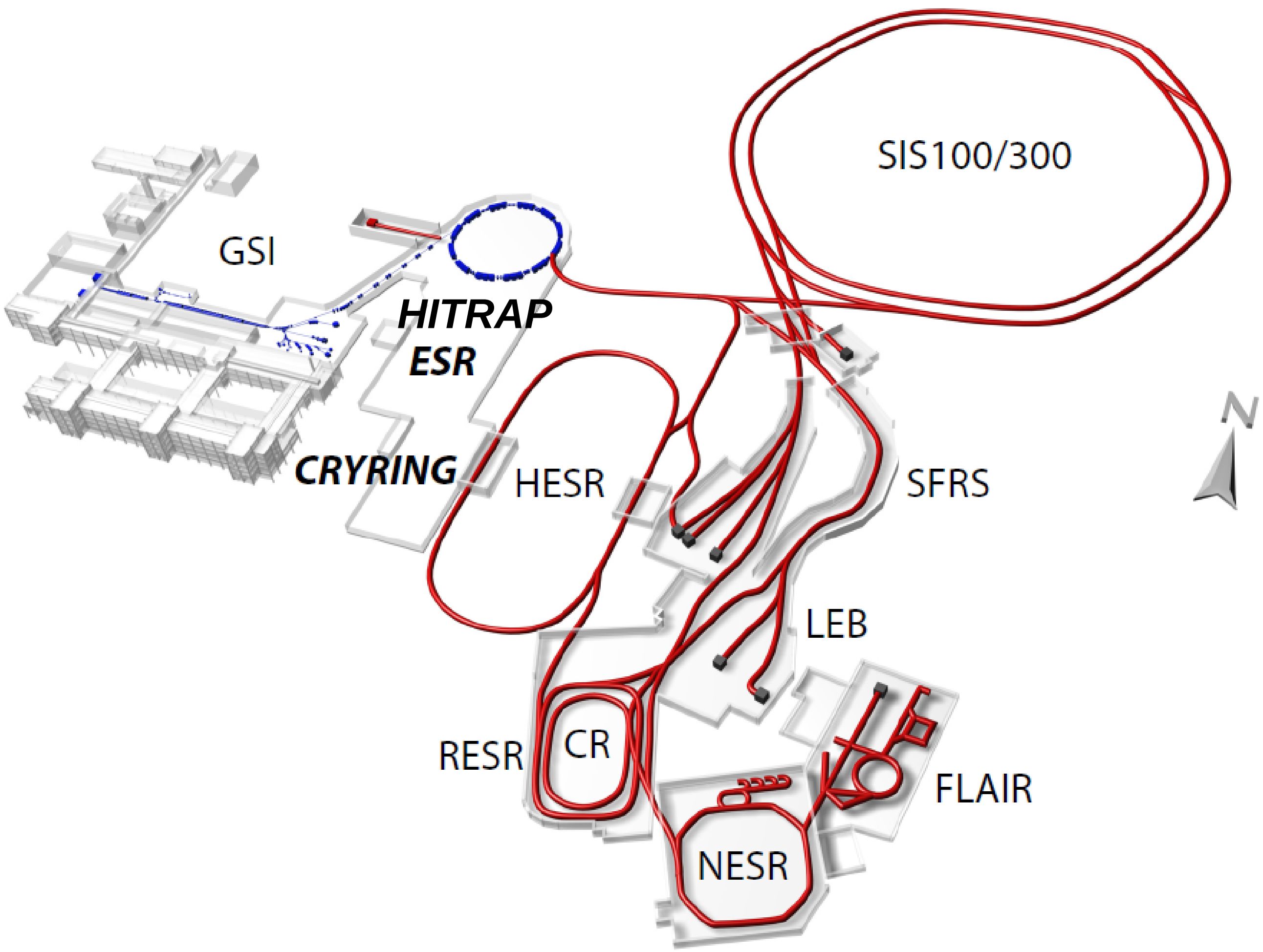
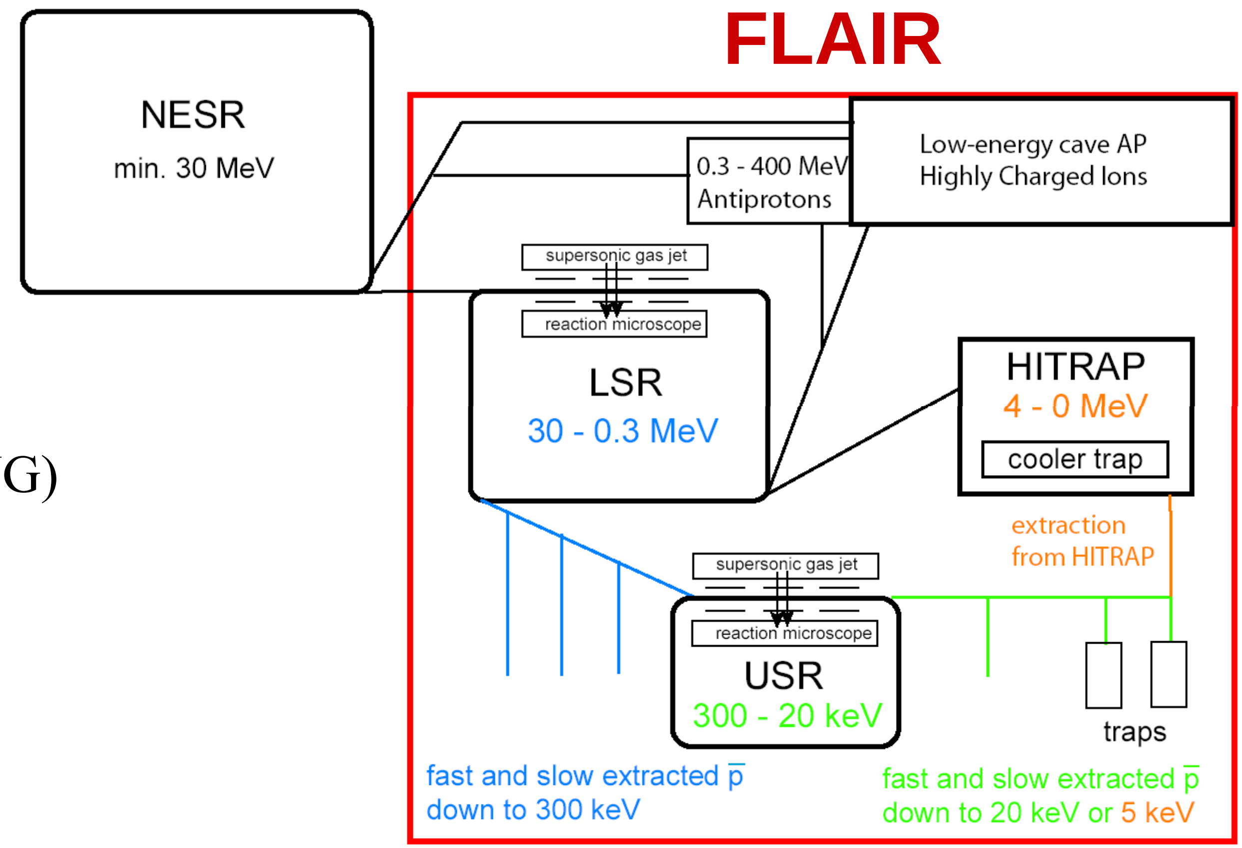
An Antigravity Experiment for the Future FLAIR Facility
(Facility for Low-Energy Antiproton and Ion Research)



Wolfgang Quint
GSI Darmstadt and Univ. Heidelberg

FLAIR - Facility for Low-Energy Antiproton and Ion Research

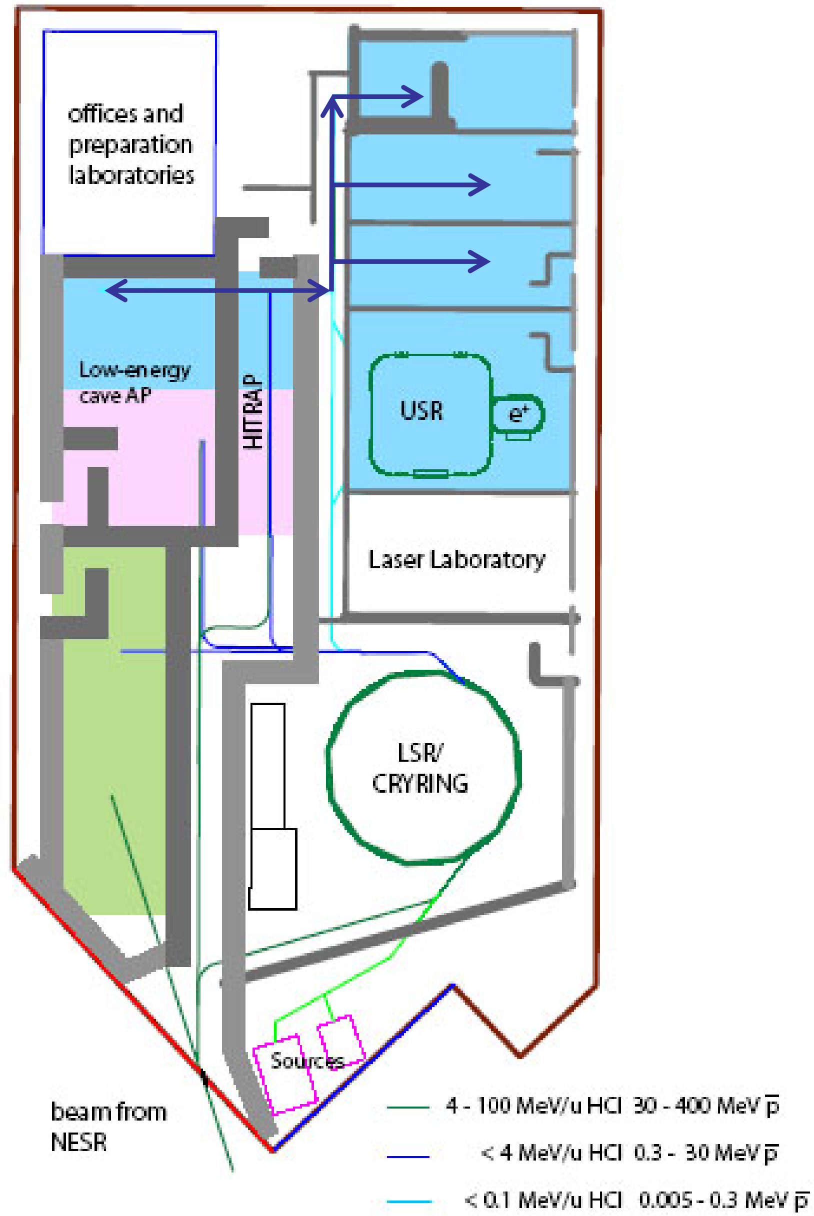
- NESR
  - Pbars and ions
  - 30 – 400 MeV
- LSR
  - Magnetic ring
  - Min. 300 keV (former CRYRING)
- USR
  - Electrostatic ring
  - Min. 20 keV
- HITRAP
  - Pbars and ions
  - Stopped & extracted @ 5 keV



energy range: 400 MeV – 1 meV

FLAIR@ FAIR - Baseline Technical Report

- High-brightness low-energy beams
- Electron cooling
- $\varepsilon \sim 1\ \pi$ mm mrad, $\Delta p/p \sim 10^{-4}$
- Storage rings with internal targets
- Slow and fast extraction
- HITRAP facility for HCI & pbar
- New experiments possible
- Same facilities can be used for highly charged ions (HCI)

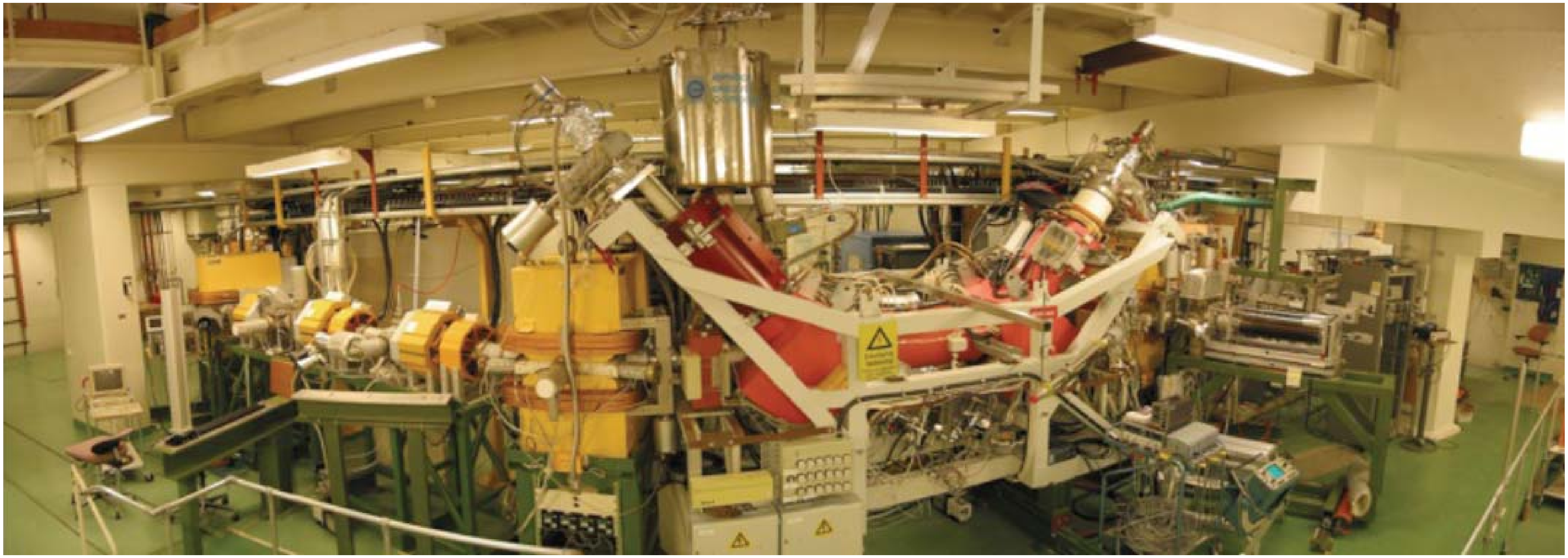


FLAIR - Facility for Low-Energy Antiproton and Ion Research

Courtesy: Horst Stöcker

Cryring (Stockholm) for LSR (Low-Energy Storage Ring) at FLAIR

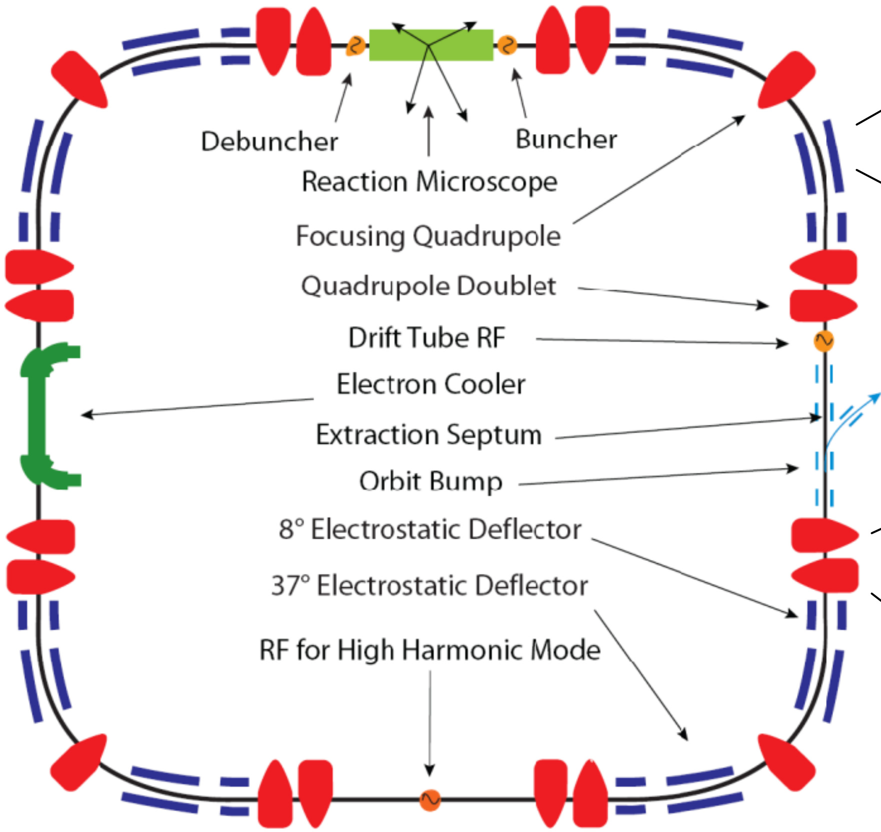
- Beam delivery for HITRAP, USR, experiments
- Fitting energy range, electron cooling
- Fast ramping, internal target
- CRYRING has been contributed by Sweden as in-kind contribution to FAIR

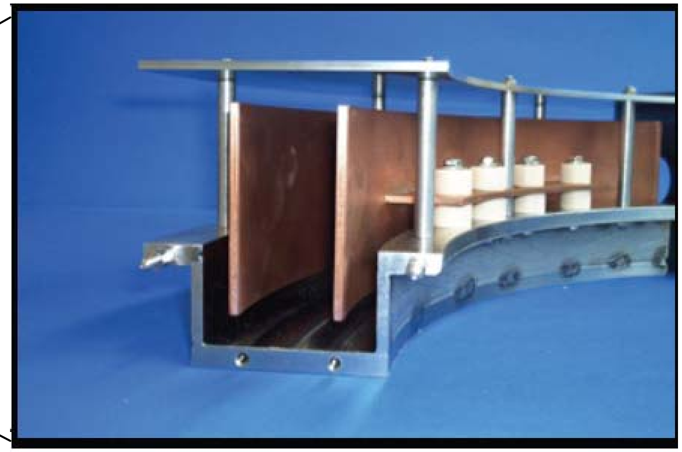


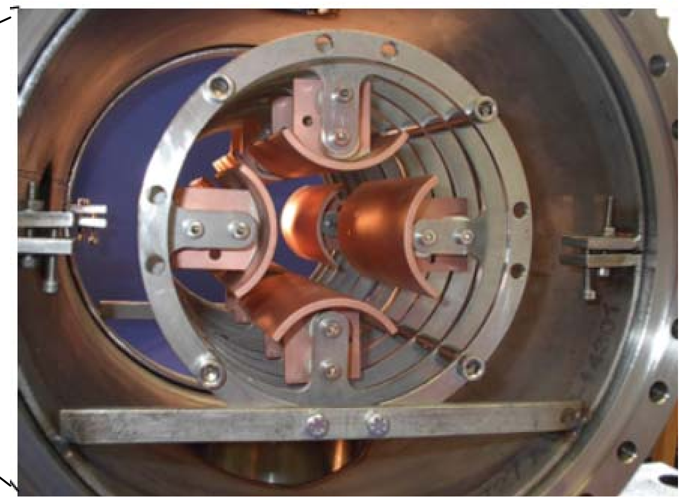
USR – Ultra-Low Energy Storage Ring

E_{min} / E_{max}	20 / 300 keV
Dimensions	8 m x 8 m
Voltages	< ± 20 kV
Number of pbars at 20 keV	$1 \cdot 10^7$

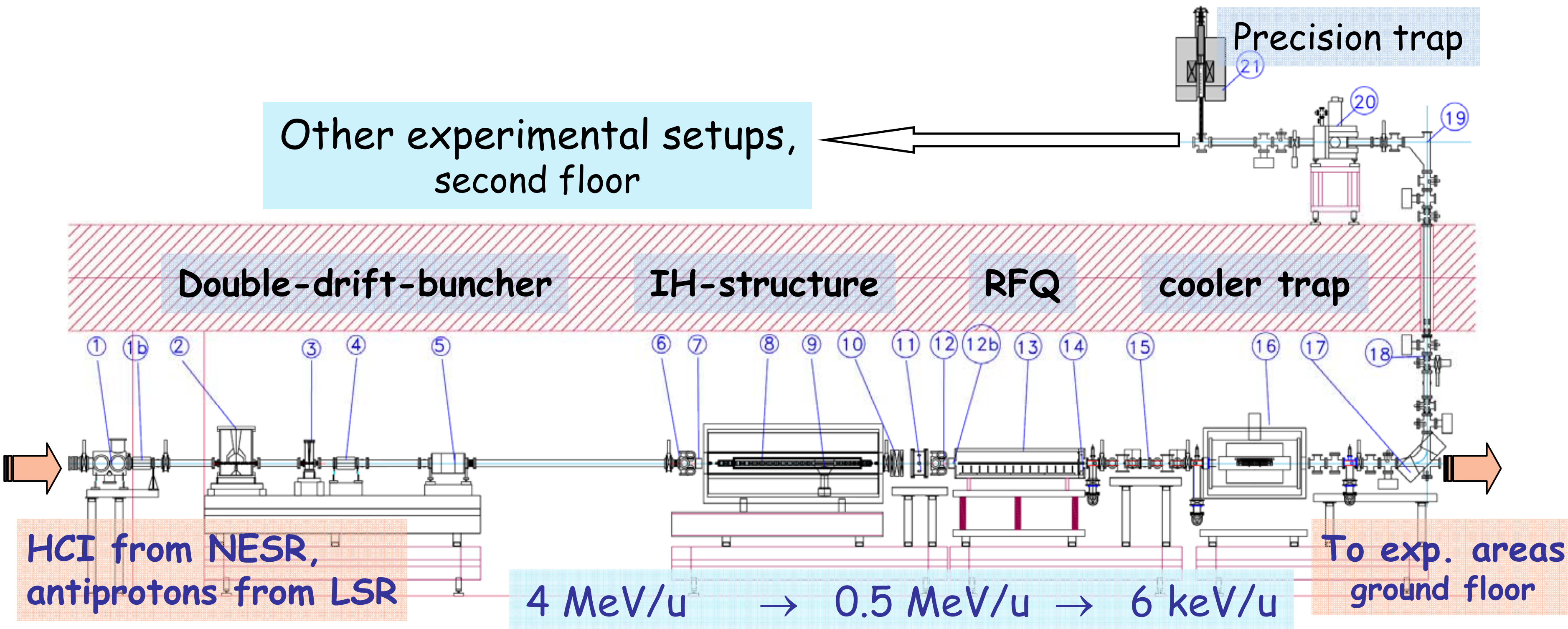
C. Welsch et al.
GSI/Cockcroft Institute Liverpool







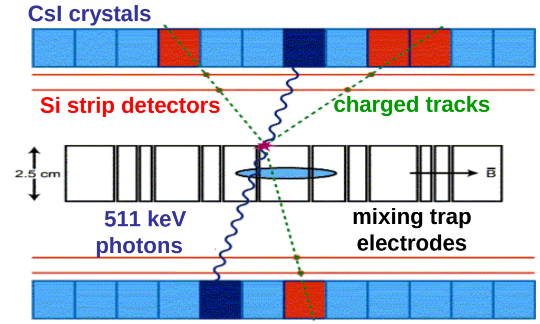
HITRAP will deliver 5 keV antiprotons to low-energy experiments



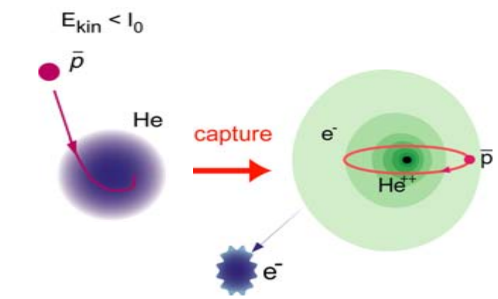
FLAIR: Research Topics with Low-Energy Antiprotons

EXPERIMENTS WITH ANTIPROTONS AT EXTREMELY LOW ENERGIES

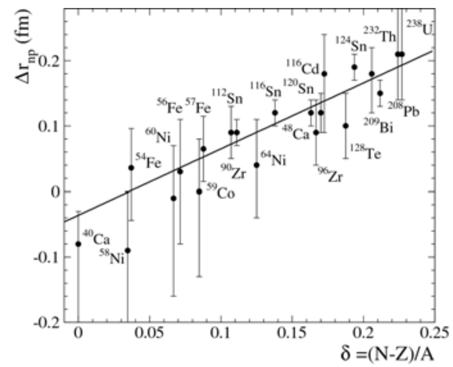
- fundamental interactions
  - CPT (antihydrogen, HFS, magnetic moment)
  - gravitation of antimatter
- atomic collision studies
  - ionization
  - energy loss
  - matter-antimatter collisions
- antiprotonic atoms
  - formation
  - strong interaction and surface effects



ATHENA Nature 419 (2002) 456



M. Hori et al., PRL 92 (2003) 123401



A. Trzcinska, J. Jastrzebski et al.PRL 87 (2001) 082501

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

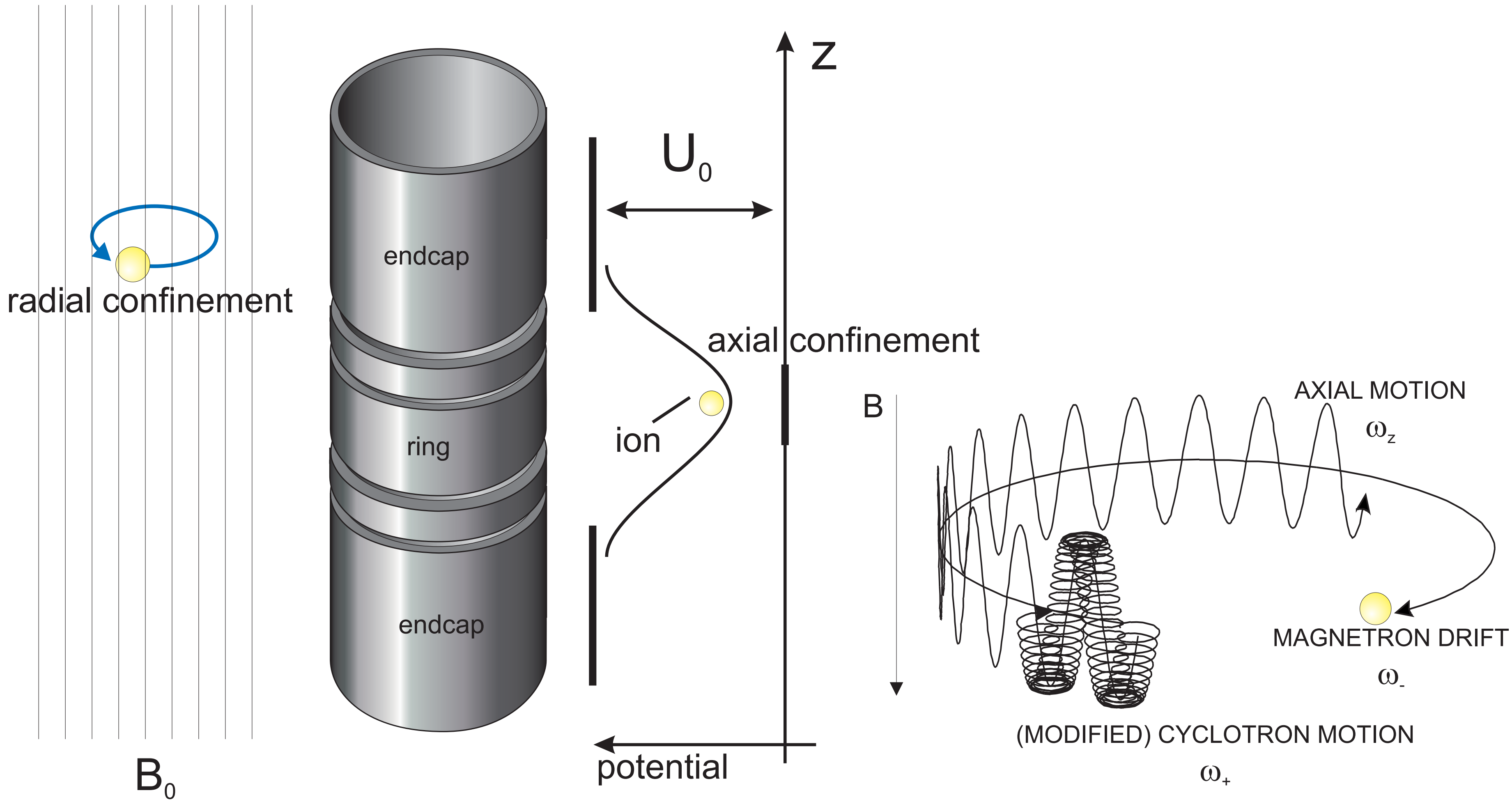
New approaches to trapping and cooling of charged particles (MPI-K and GSI/FLAIR) with general methods of trapping and cooling of neutral atoms (Univ. of Texas at Austin)

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.

Tasks to Charged Particle Storage

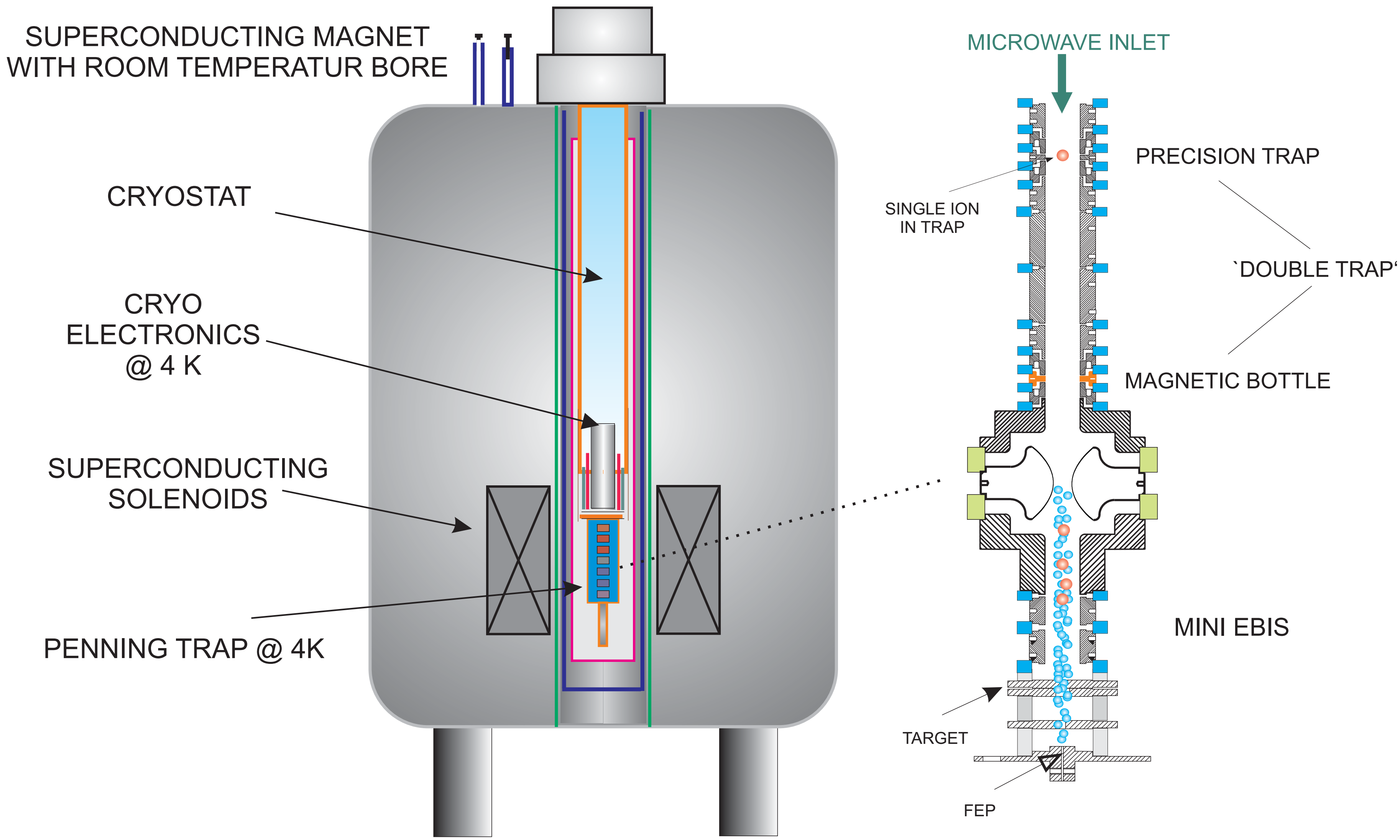
- Storage of a large number of protons and electrons → 10^8
- Sensitive non-destructive detection → 1
- Fast cooling of the charged particles → ms-s
- Efficient cooling of antiprotons → ???

Single Charged Particle Stored in a Penning Trap

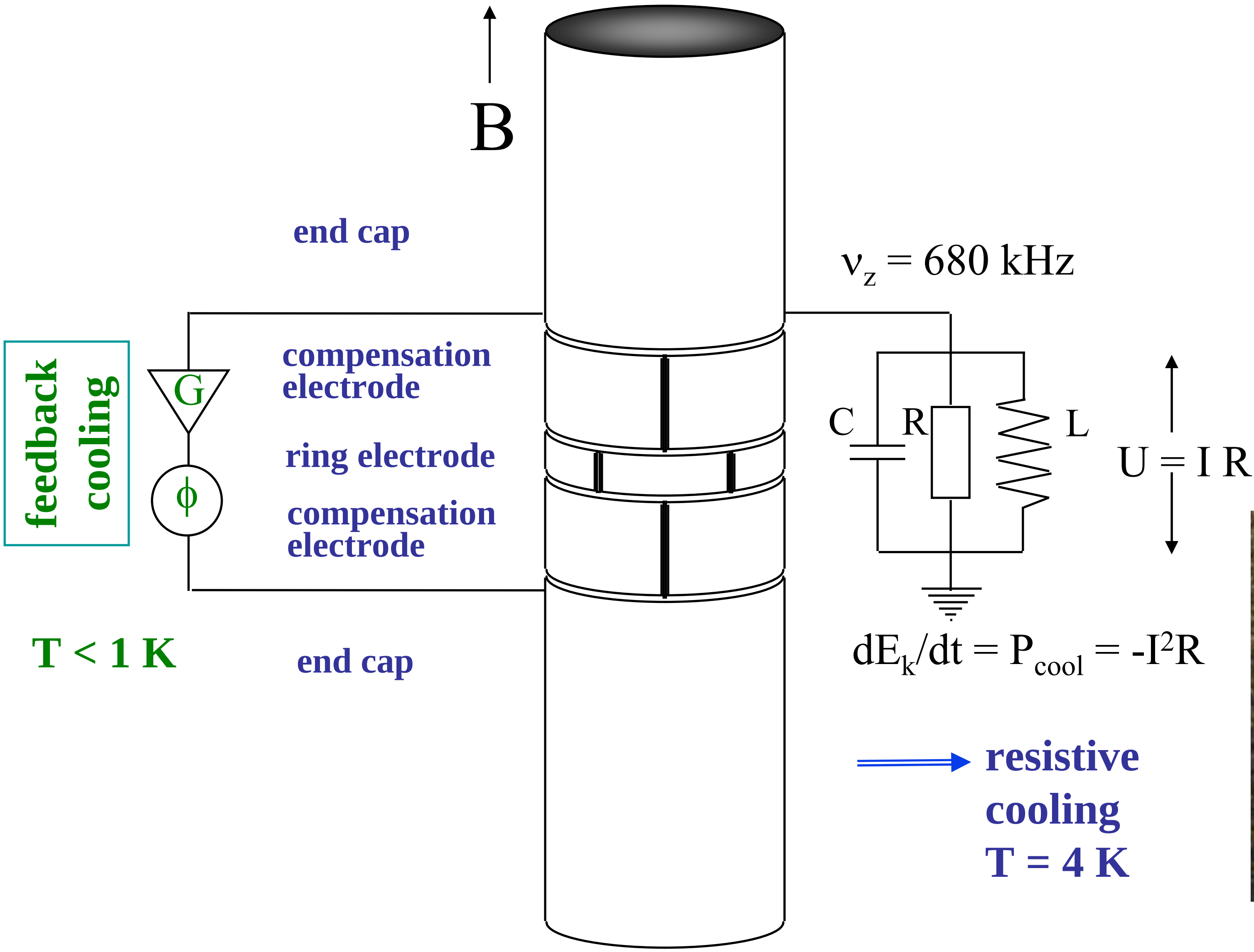


magnetic | physical | electric | combined ion motion

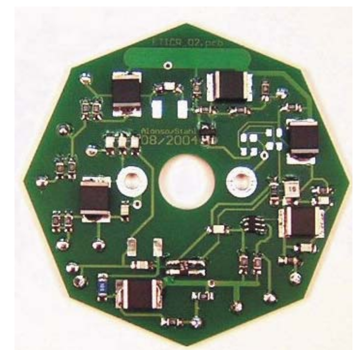
Highly Charged Ion g-Factor Apparatus at Mainz (Coll. GSI + MPI-K): Tests of Quantum Electrodynamics in Strong Fields

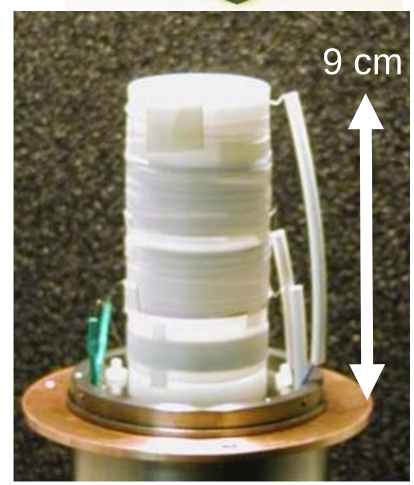


Electronic detection of a single trapped ion: Resistive cooling to 4 K and active feedback cooling to < 1 K

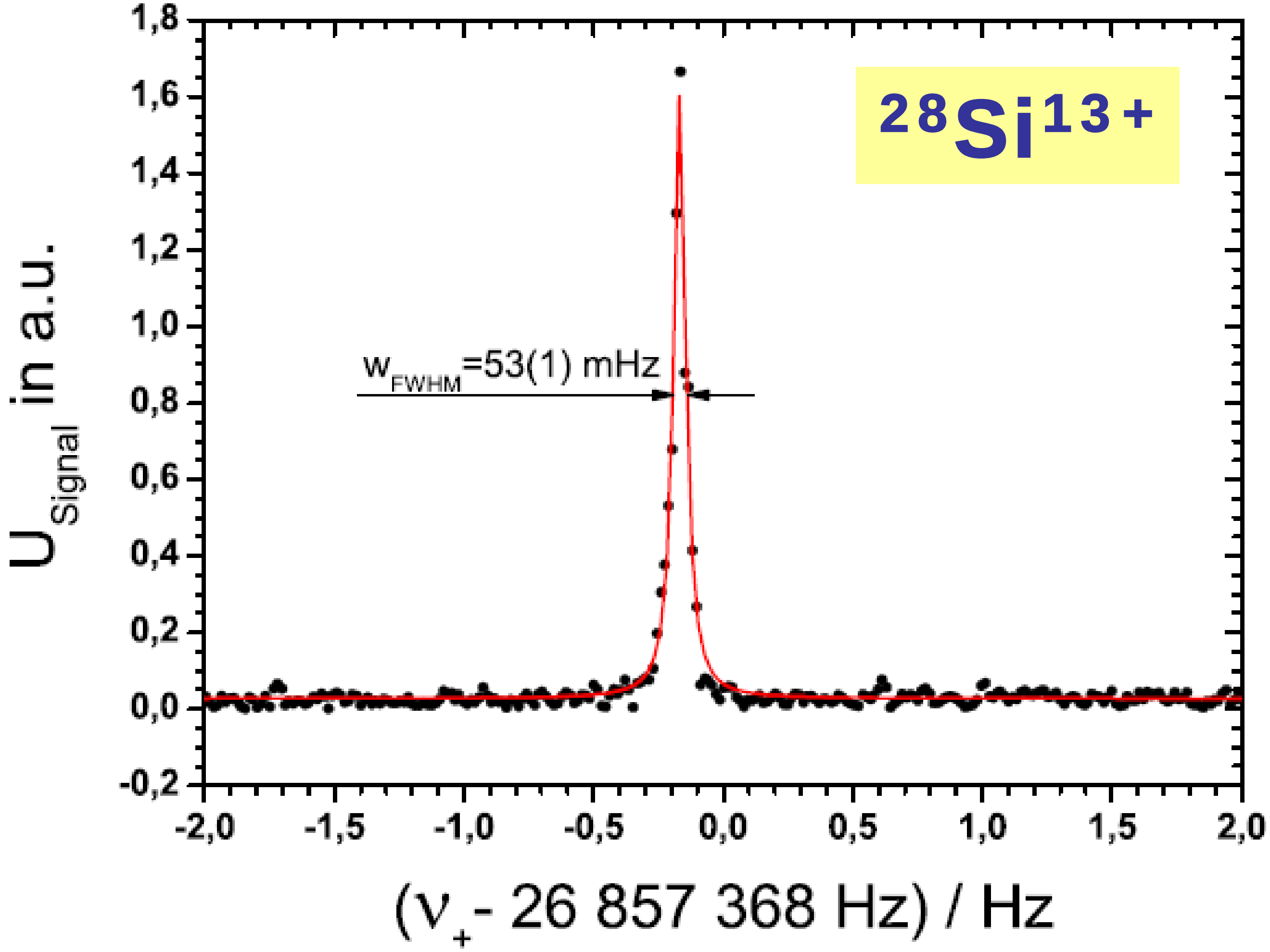


complex electronics



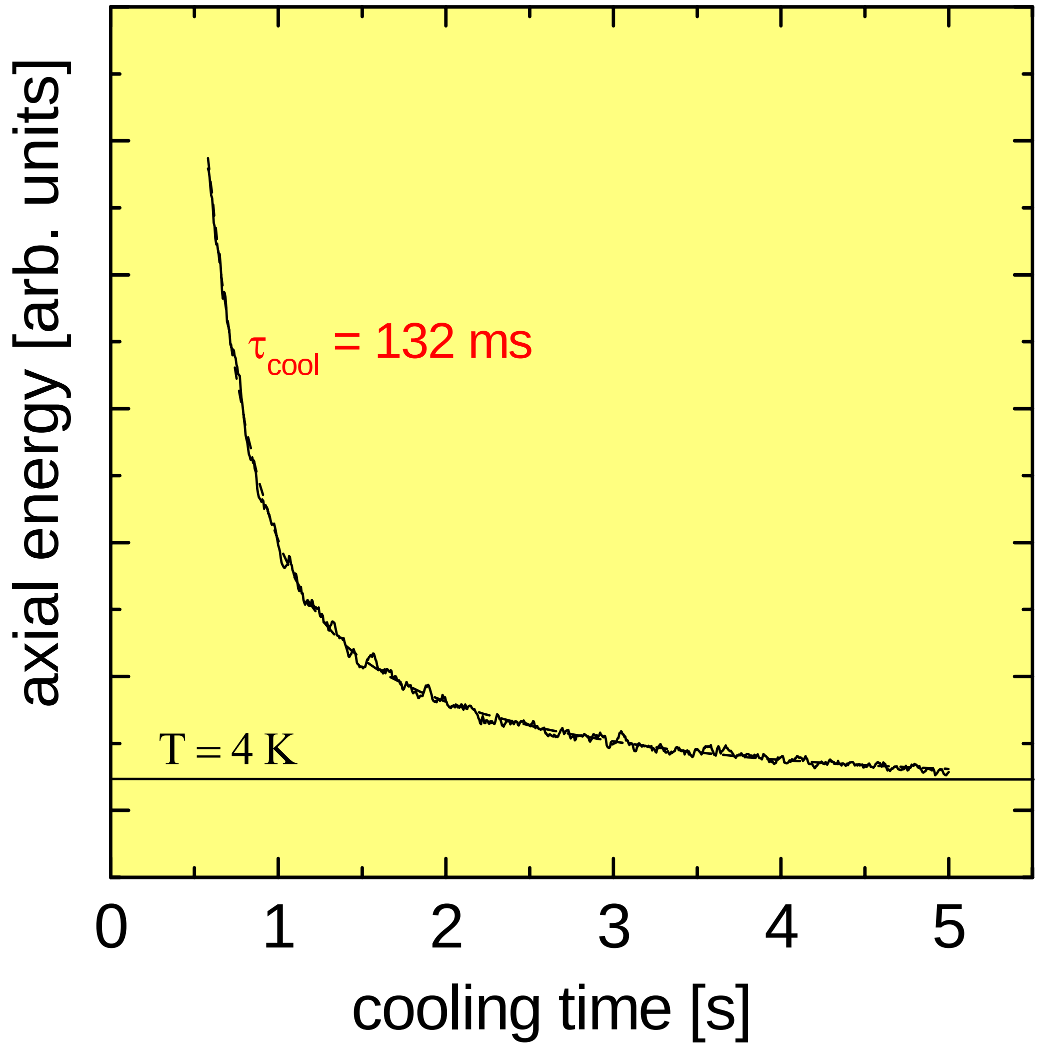


High-resolution cyclotron frequency measurement of a single highly charged silicon ion



Resistive Cooling of Trapped $^{12}C^{5+}$ Ions to T = 4 K

- final temperature: T = 4 Kelvin



Determination of the (Anti)Proton g-Factor
BASE Collaboration at AD/CERN, Spokesperson: Stefan Ulmer

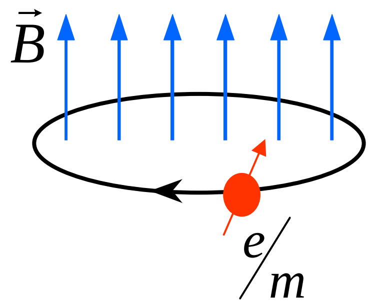
$$\omega_c = \frac{e}{m_p} B$$

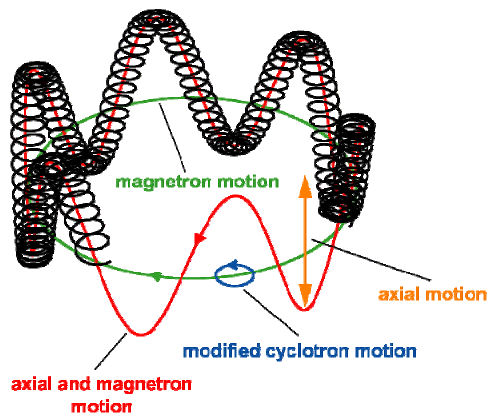
Cyclotron frequency

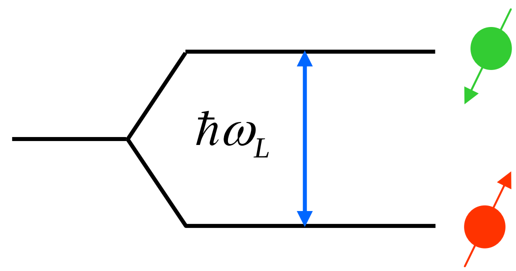
$$g = 2\,\frac{\omega_L}{\omega_c}$$

$$\omega_L = g \frac{e}{2m_p} B$$

Larmor frequency



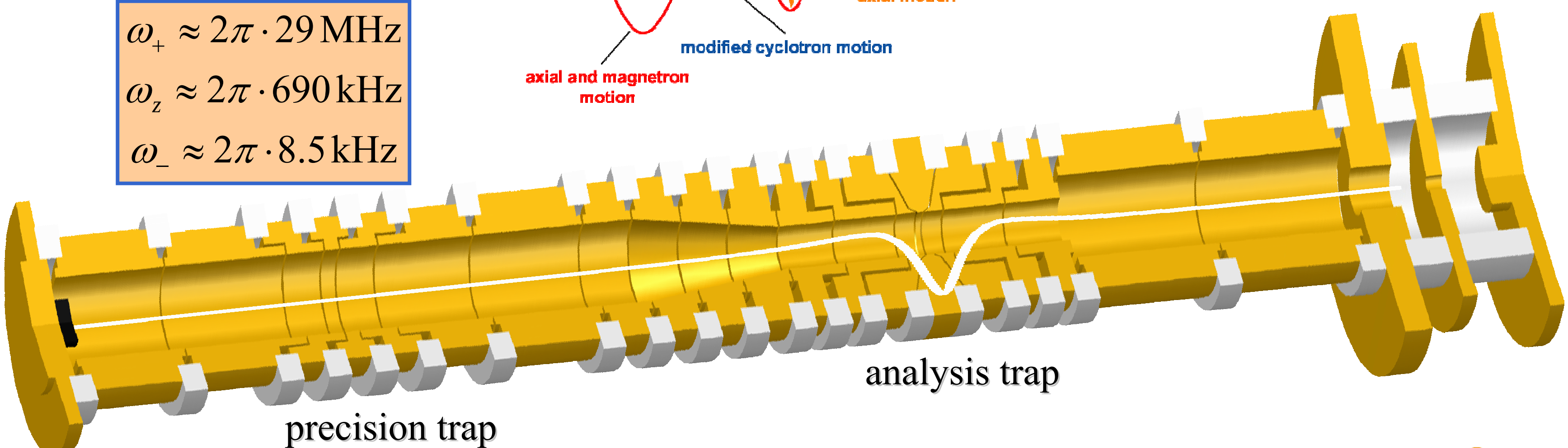




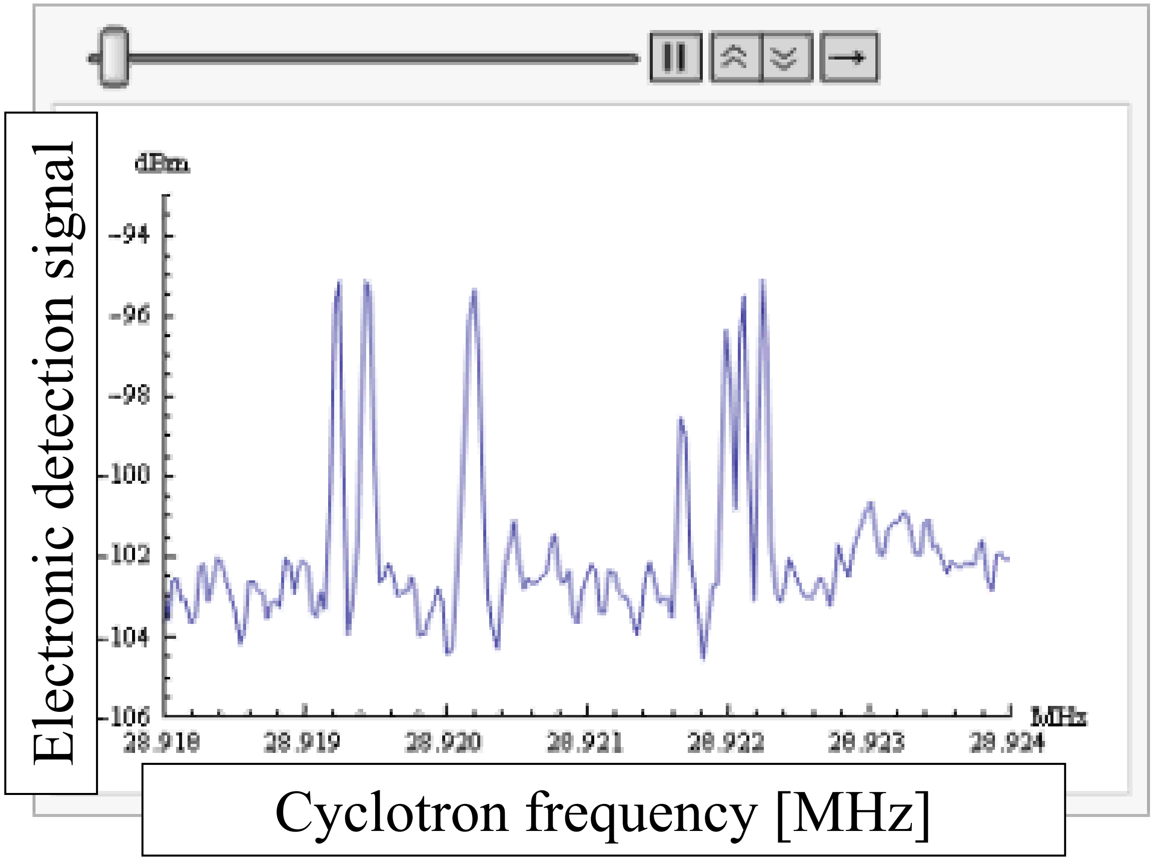
$$\omega_c = \sqrt{\omega_+^2 + \omega_-^2 + \omega_z^2}$$

$$\omega_+ \approx 2\pi \cdot 29\,\text{MHz}$$
$$\omega_z \approx 2\pi \cdot 690\,\text{kHz}$$
$$\omega_- \approx 2\pi \cdot 8.5\,\text{kHz}$$

$$\omega'_z(\uparrow) - \omega'_z(\downarrow) = \Delta\omega_z$$



Evaporative Cooling of Protons



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

Sympathetic Evaporative Cooling

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. Evaporative cooling can be conveniently done by tuning of a photo-detachment laser.

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]

[1]*Departamento de Física Atómica Molecular y Nuclear, Universidad de Granada, 18071 Granada, Spain*
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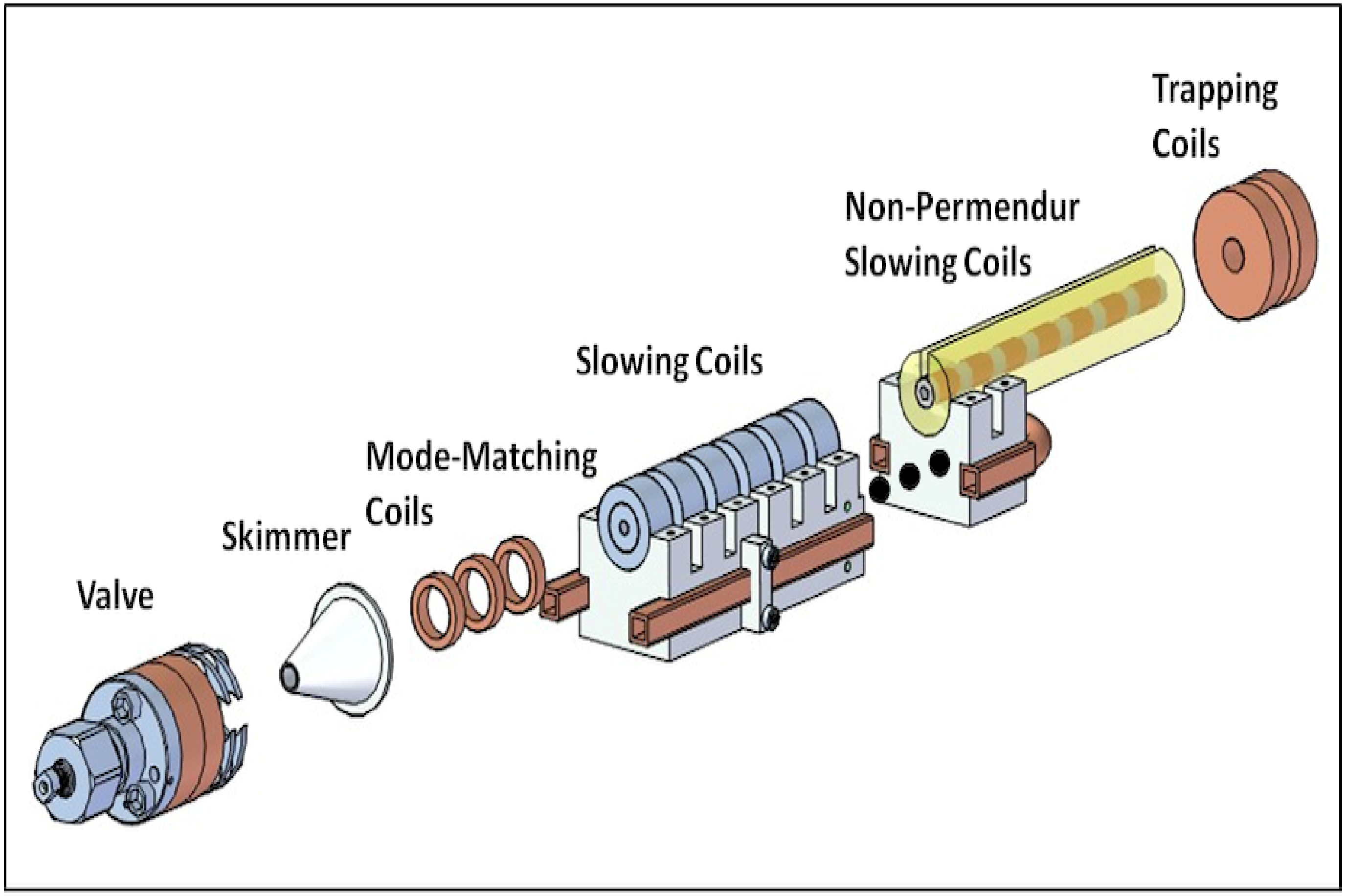
[5]*GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*

Tasks to Neutral Particle Storage

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

Ref.: M. Raizen, Univ. of Texas at Austin

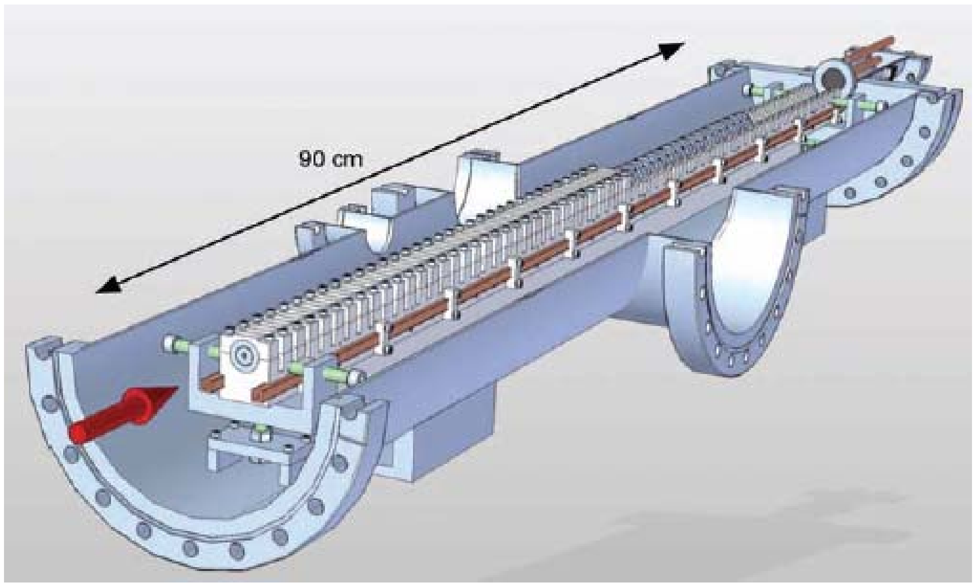
Towards Magnetic Trapping



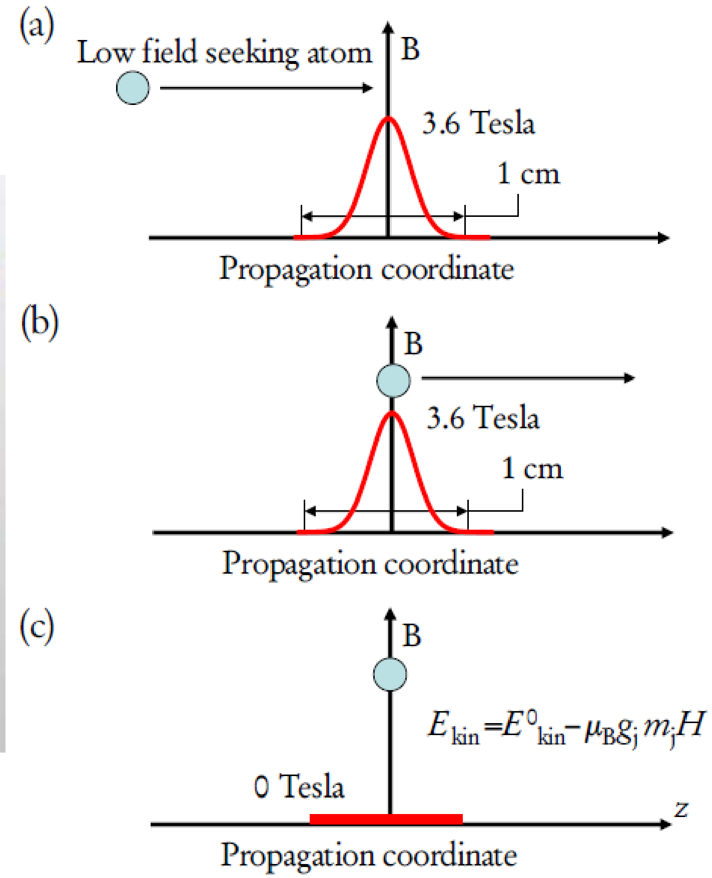
Ref.: M. Raizen

Atomic Coilgun

- Directly slow and stop a beam of paramagnetic atoms



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



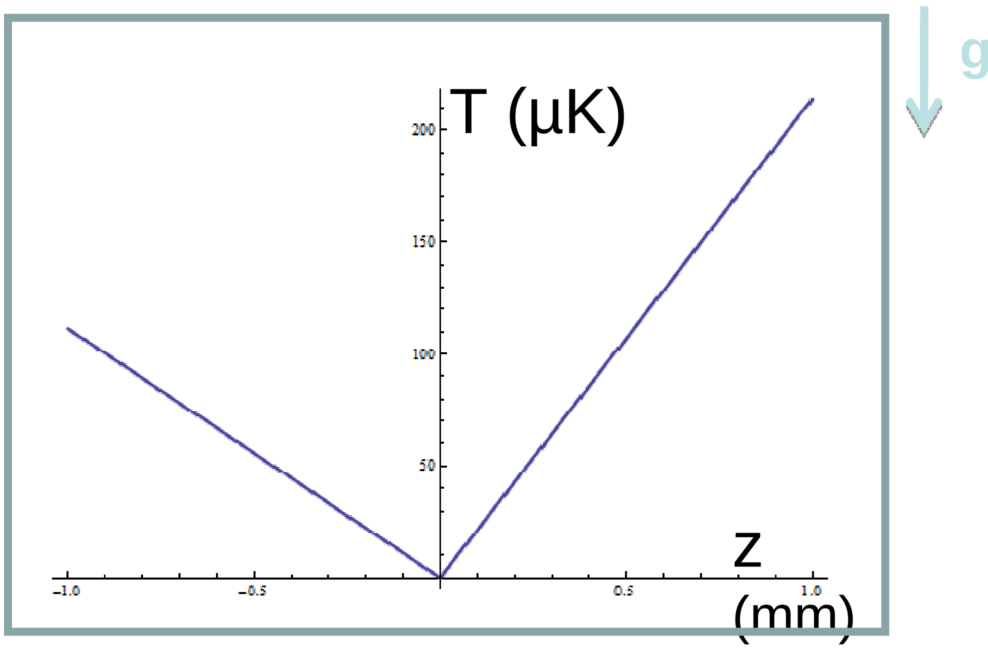
Efficiency: 2-10%   Temperature: 80 mK

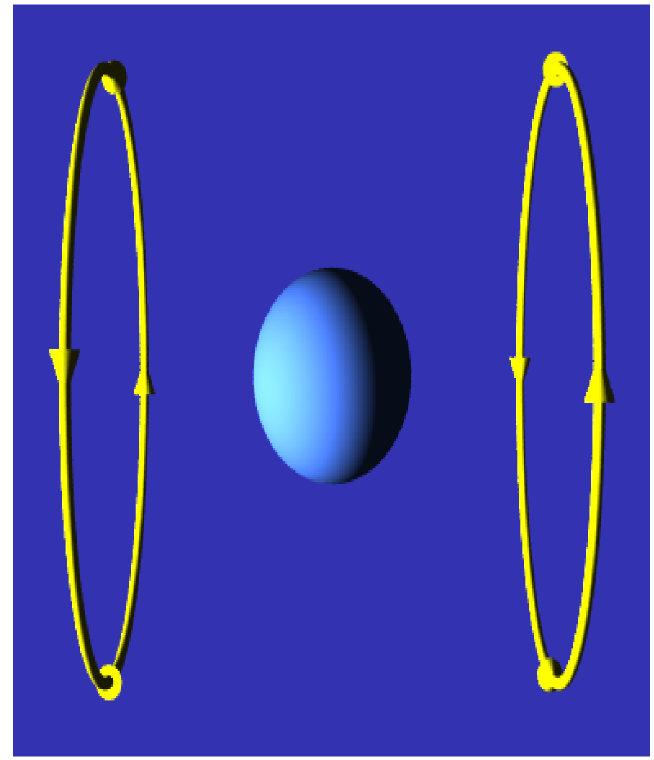
Most atoms in periodic table elements are paramagnetic

Ref.: M. Raizen

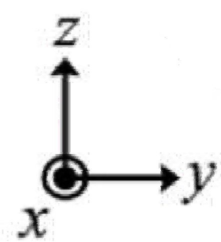
E. Narevicius *et al*., Phys. Rev. Lett. 100, 093003 (2008)

Atom Trapping



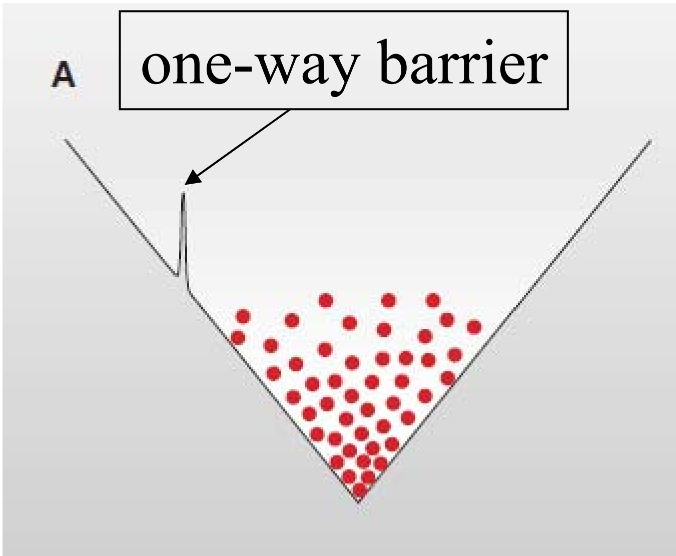


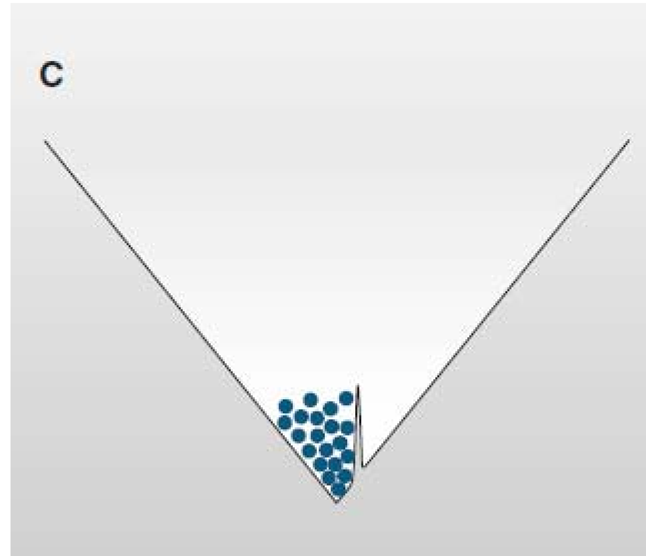
$$E = \mu_B \,|\, B \,|\, + mgz$$

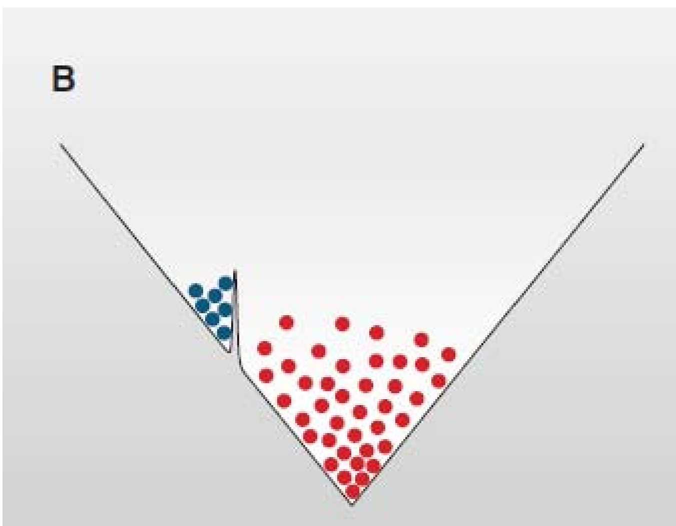


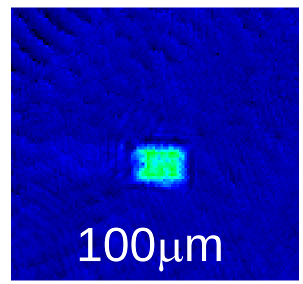
Ref.: M. Raizen

Single-Photon Atomic Cooling by One-Way Barrier
→ Maxwell's Demon









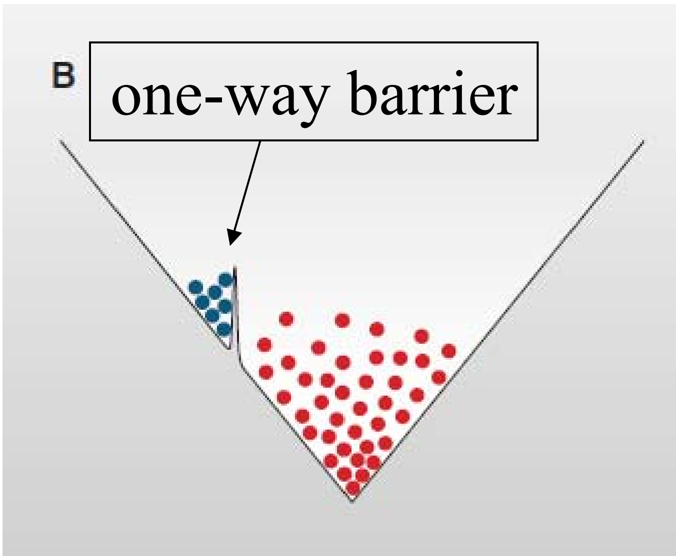
T ~ a few mK

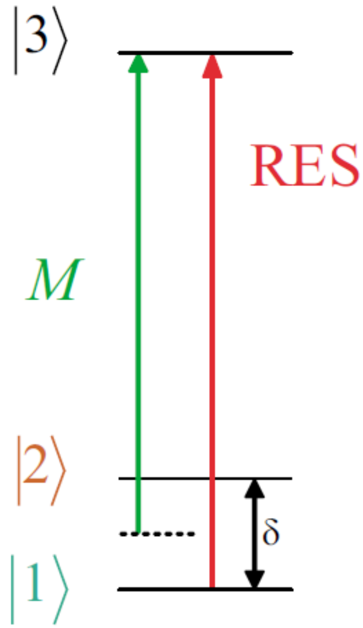
350x increase in phase space density from magnetic trap!

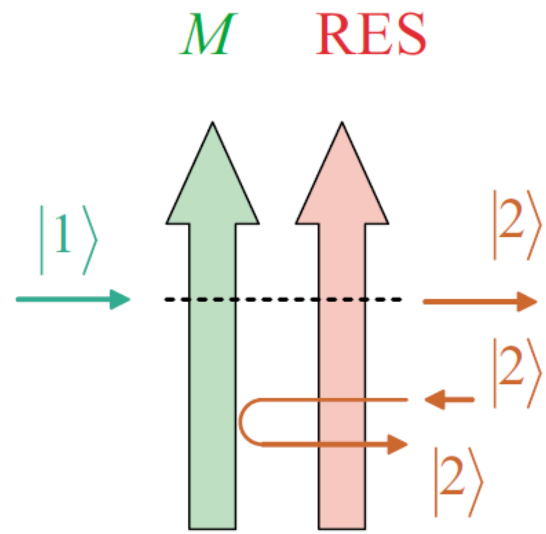
G. Price et al., Phys. Rev. Lett. 100, 093003 (2008)

Ref.: M. Raizen, Science 324, 1403 (2009)

Single-Photon Atomic Cooling by One-Way Barrier → Maxwell's Demon





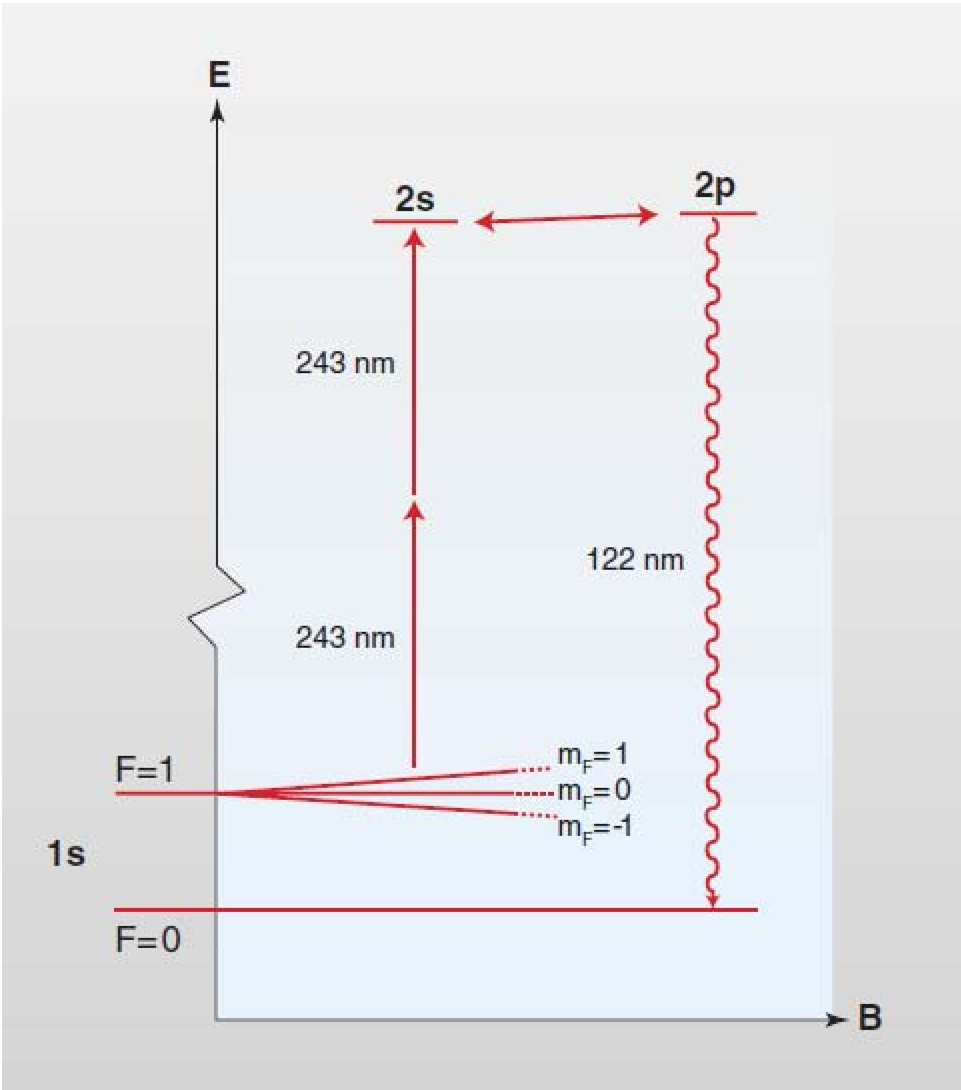


Key points:

- Laser beam M is attractive for state 1, but repulsive for state 2.
- Laser beam RES optically pumps into state 2.

Ref.: M. Raizen et al., PRL 94, 053003 (2005)

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.
3) Frequency doubling in a resonant build-up cavity to λ = 243 nm.
→ 5 mW output power.
4) Confocal build-up cavity around the atoms.
→ 100x power increase.

Ref.: M. Raizen

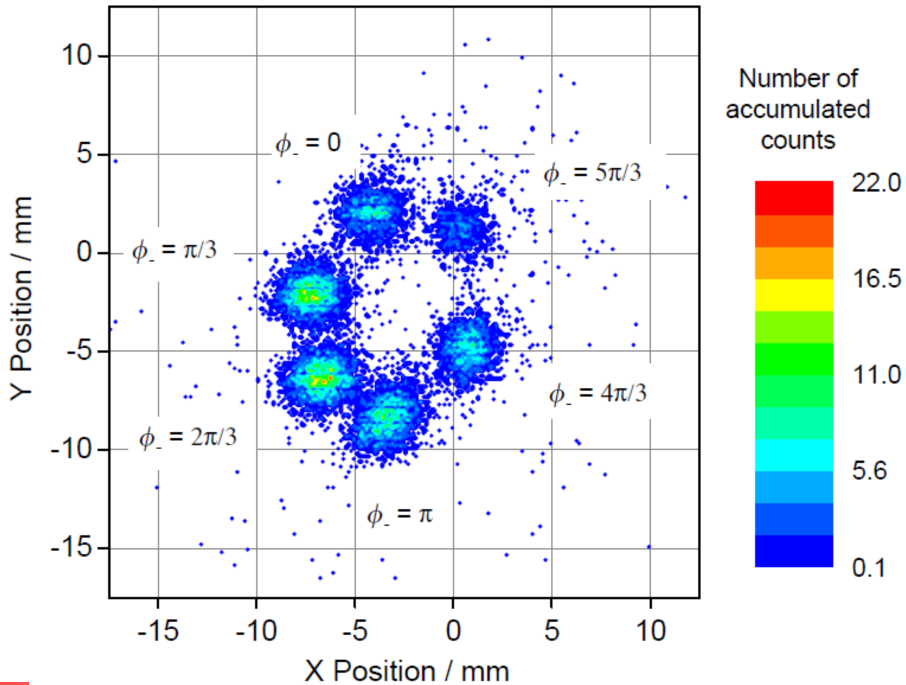
Precision Measurement of gbar/g

- Excite H-bar to 2S state (lifetime 120 ms)
- Raman interferometry (see talk by Susannah Dickerson) between hyperfine states of 2S (177 MHz)
- Raman laser beams at 657 nm (near 2S-3P transition)
- 1000 atoms, T = 30 ms: g-bar/g = 2 x 10^{-7} per shot
  Averaging over one year @ 40 shots per day: reach 5x10^{-9}

Ref.: M. Raizen

Detection of Neutral Stored Hydrogen Atoms

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)

Ref.: M. Raizen

Summary

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**

Thanks a lot for the invitation and your attention!

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Announcement of FLAIR Collaboration Meeting and Workshop: 15/16 May 2014 at MPI-K Heidelberg

Topics:

- Experiments with antiprotons and antihydrogen
- Highly charged ions in traps and rings for spectroscopy
- Interaction of low-energy highly charged ions and pbars with targets
- Advances in theory of antimatter and exotic ions
- Nuclear and particle physics with antiprotons
- Heavy-ion experiments, ion surface interactions, collision dynamics
- Antiprotonic atom X-ray spectroscopy
- New instrumentation and facilities

FLAIR: Antiproton Intensities

SIS 100: acceleration of 2.8×10^{13} protons, E = 29 GeV

Antiproton target: production of 1.0×10^{8} pbars/ 5 s, E = 3 GeV

Collector ring CR: fast stochastic cooling in 10 s, N = 10^{8}/cycle

RESR: accumulation of pbars, N = $10^{8} – 10^{11}$

NESR: electron cooling, deceleration from 3 GeV to 30 MeV

FLAIR

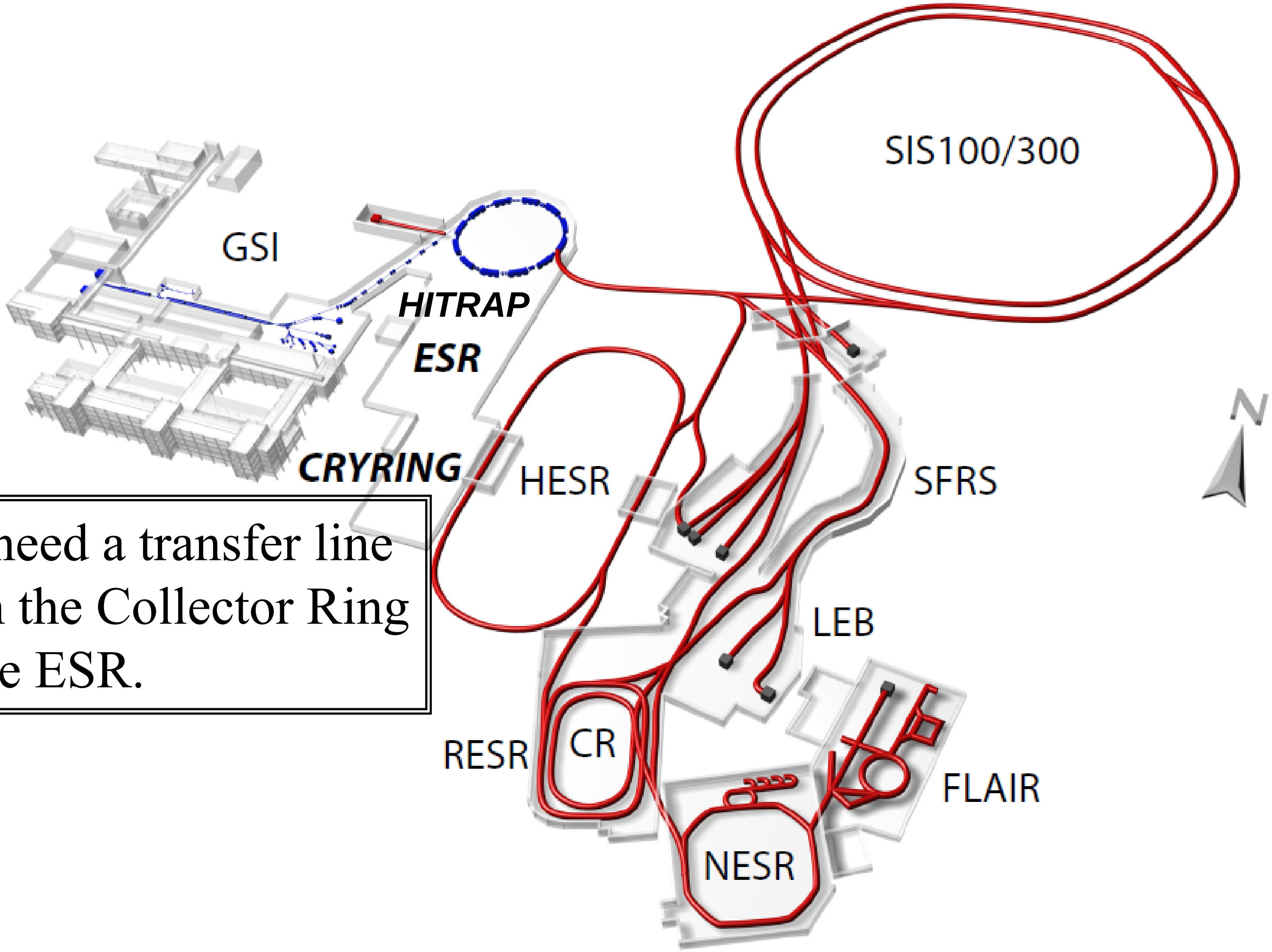
LSR: deceleration from 30 to 0.3 MeV

HITRAP: deceleration from 4 MeV to rest, av. intensity: $1x10^{6}$/s

USR: deceleration from 300 to 20 keV, av. intensities:
- R_{eff} = $1x10^{12}$/s at 300 keV
- R_{extr} = $1x10^{6}$ /s at 300 keV
- R_{eff} = $1x10^{10}$/s at 20 keV
- R_{extr} = $5x10^{5}$ /s at 20 keV

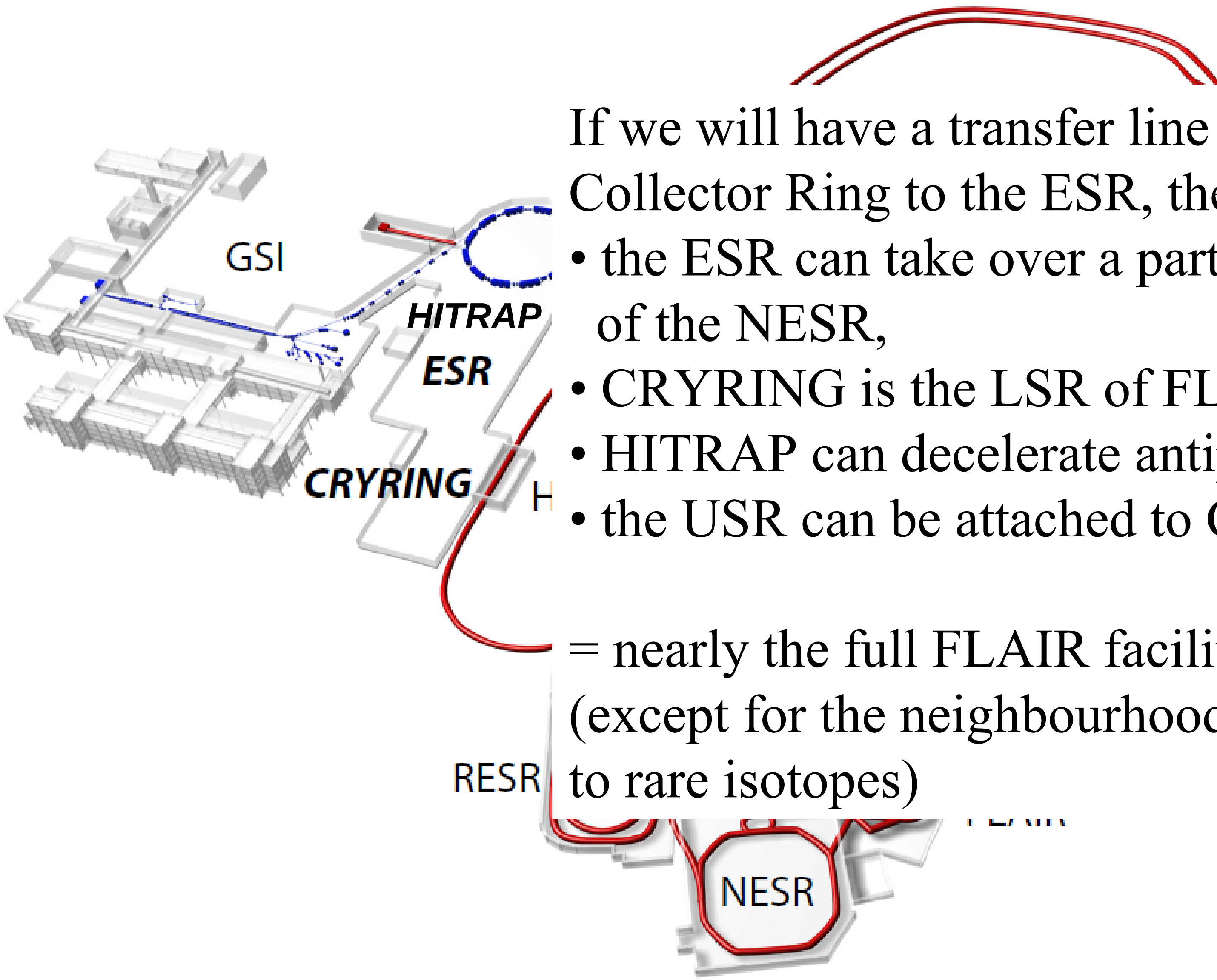
pbar experimental areas: E = 400 MeV to 5 keV

FLAIR - Facility for Low-Energy Antiproton and Ion Research



We need a transfer line from the Collector Ring to the ESR.

Alternative for the Implementation of FLAIR



If we will have a transfer line from the Collector Ring to the ESR, then

- the ESR can take over a part of the tasks of the NESR,
- CRYRING is the LSR of FLAIR,
- HITRAP can decelerate antiprotons, and
- the USR can be attached to CRYRING.

= nearly the full FLAIR facility (except for the neighbourhood to rare isotopes)