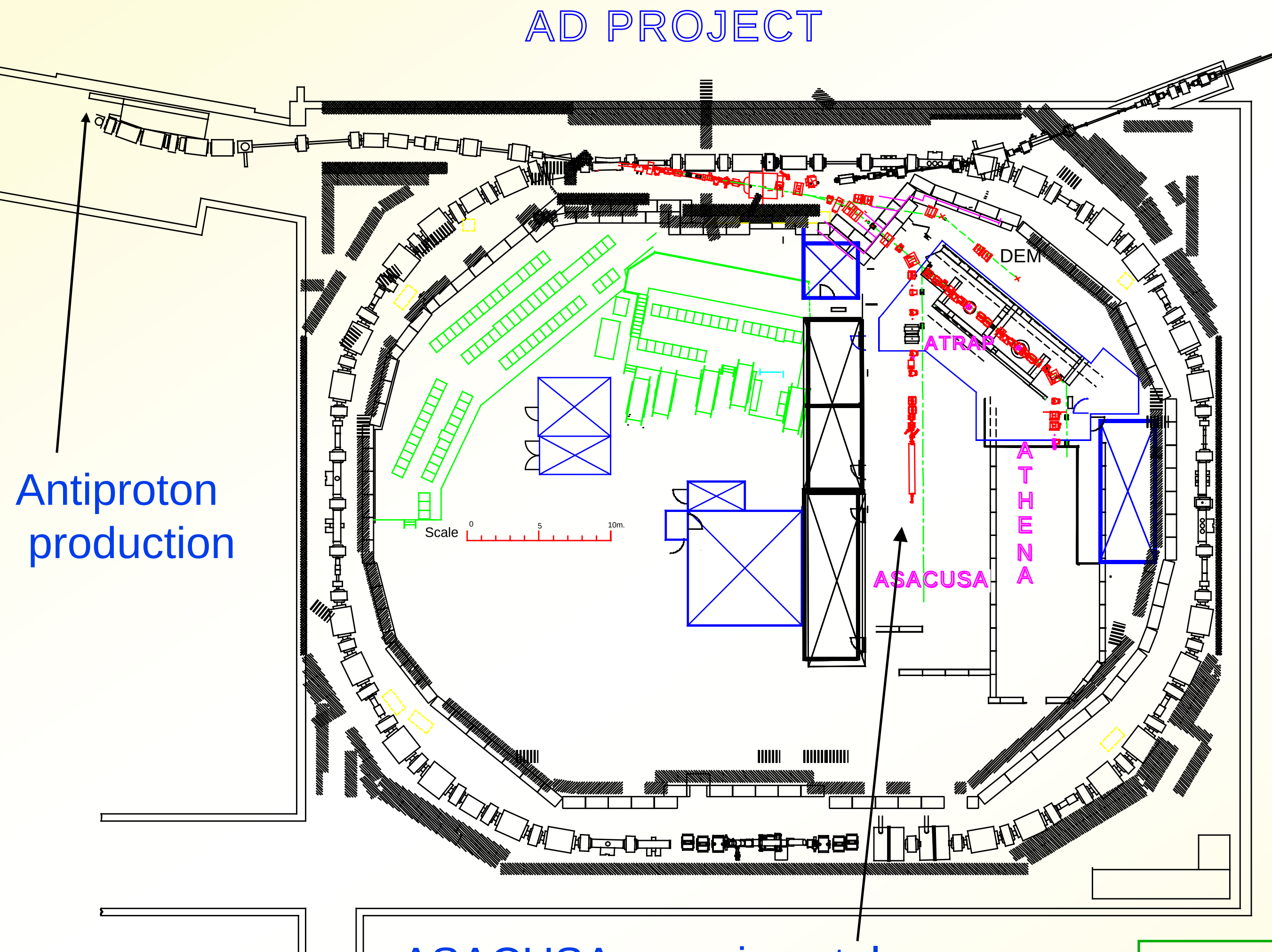
Exotic Atomic Systems in Traps

E. Widmann
University of Tokyo

HITRAP Workshop, GSI, 11. Dezember 2002

- Antiprotonic Atoms: Spectroscopy and Collision
- Experience with ASACUSA RFQD & Catching Trap @ CERN/AD
- Experiments at HITRAP / GSI Future Facility
  - Antihydrogen for CPT and Gravitation Measurements
  - Antiprotonic Radioactive Isotopes for Nuclear Physics
  - Low-energy antiproton beams via extraction from a trap for atomic collision experiments

Antiproton Decelerator (AD) at CERN: 5 MeV



Antiproton production

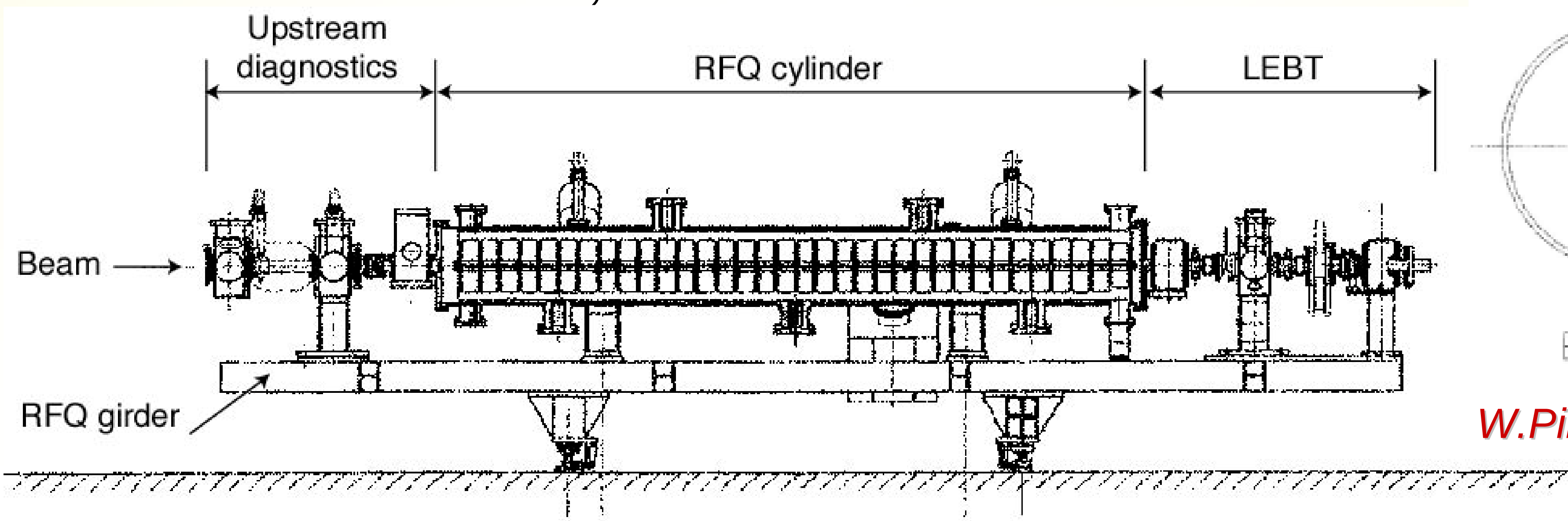
ASACUSA experimental area

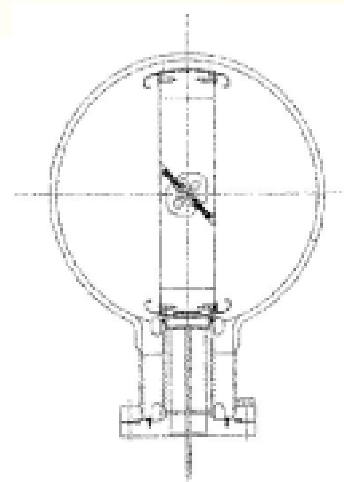
- Started operation July 6th, 2000
- Antiproton capture, deceleration, cooling
  - 100 MeV/c (5.3 MeV)
- Pulsed extraction
  - 2-4 x 10^7 antiprotons per pulse of 100 ns length
  - 1 pulse / 100 seconds
- Antiprotonic atom formation and spectroscopy incl. Antihydrogen (ATRAP, ATHENA

Future after 2005 uncertain

ASACUSA
Radio Frequency Quadrupole Decelerator: 50 keV

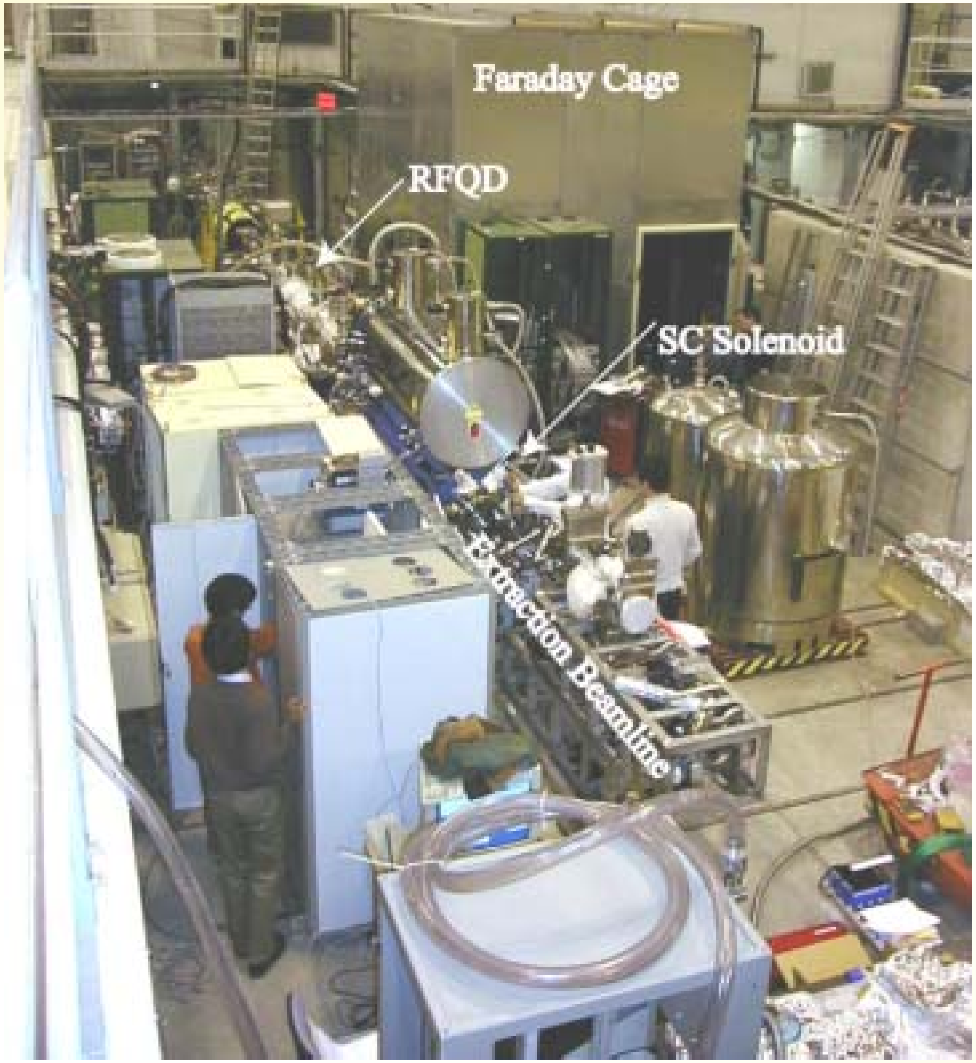
- Decelerate antiprotons from 5.3 MeV to 63 keV
  - *Buncher + HEBT + Energy corrector + 200 MHz RFQ + LEBT*
  - *Beam emittances essentially preserved*
  - *Transmission (deceleration efficiency) 25 – 40 %*
  - *Variable output energy 10 keV – 120 keV*
  - *Tested at Aarhus, commissioned at CERN late 2000*





W.Pirkl et.al.

RFQD + pbar Catching Trap

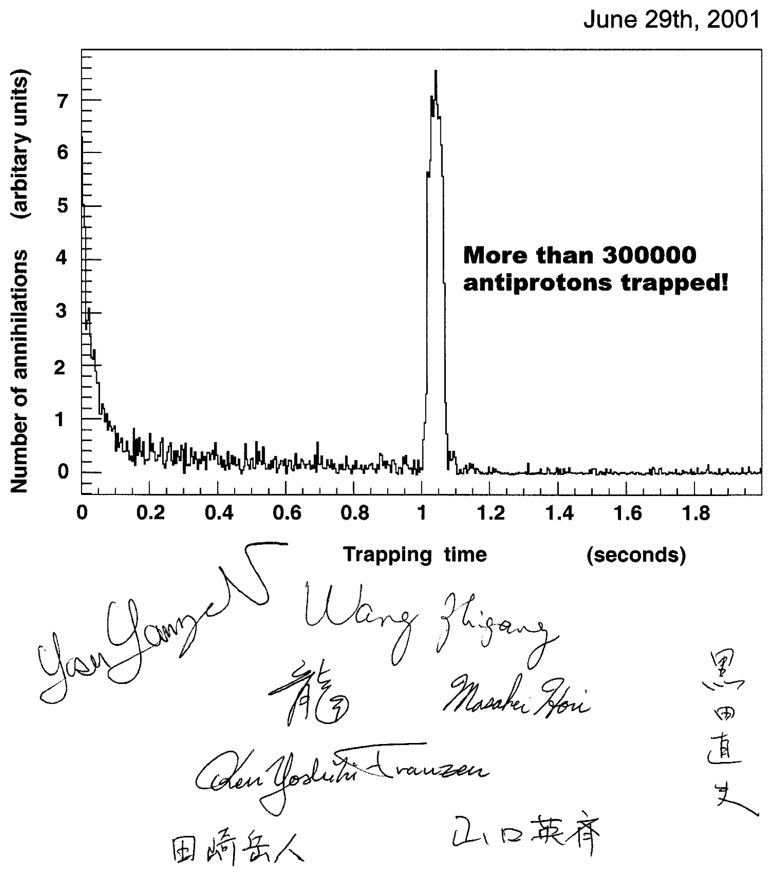


- Inject 100 keV beam from RFQD into a 5 T solenoid magnet
- Degrade by a foil to 10 keV
- Trap, electron cool to a few eV and compress
- Extract at desired energy (10-1000 eV)
- Transport to experimental region (high pressure, low field)

Y. Yamazaki et al., U Tokyo (Komaba)

Antiprotons Trapping & Cooling

First antiprotons trapped by ASACUSA collaboration!



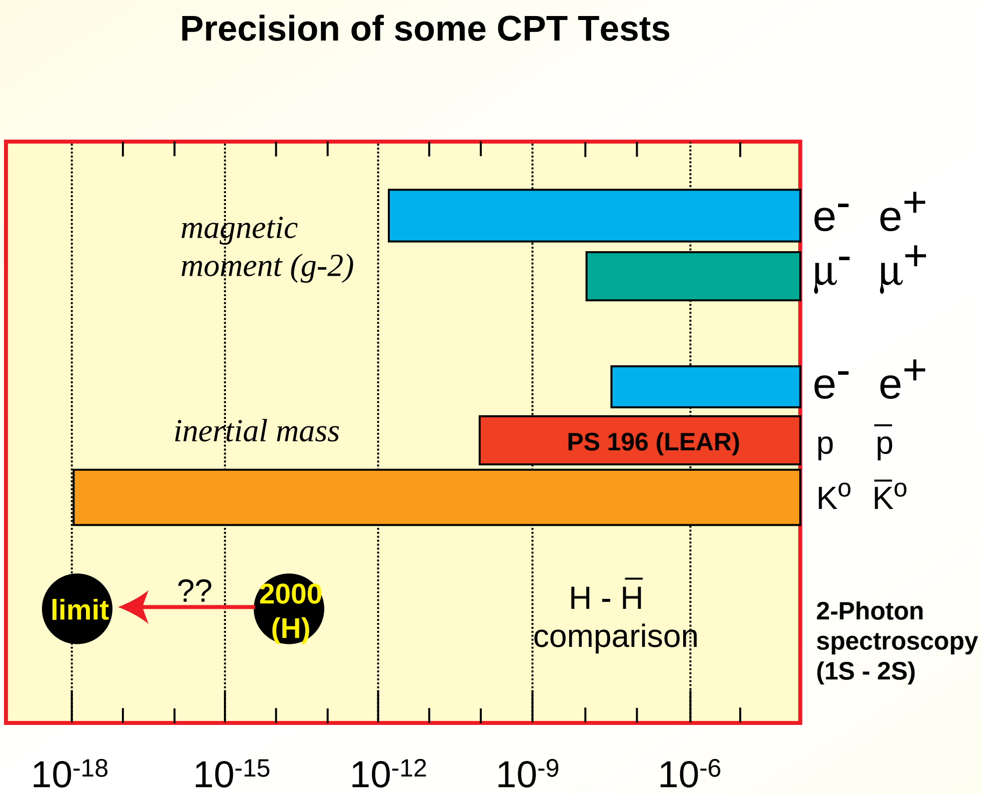
- Combination of RFQD (deceleration efficiency 25 - 40 %) and large catching trap allows capture of 2×10^6 antiprotons and more from a single AD shot
- Factor 100 more than other experients
- Cooling of antiprotons successfully achieved
- Commissioning now continuing at AD
- Efficiency
  - 10% of antiprotons in AD

HITRAP and Antiprotons

- HITRAP deceleration scheme similar to ASACUSA scheme at AD
  - 7 MeV – LINAC – RFQD – Catching & Cooling Trap – Precision Trap
- Increased production rate at GSI
  - Several 10^7 / second vs. $2x10^7$ / 100 s
- Experiments
  - Antihydrogen for CPT tests and gravity
  - Antiprotonic radioactive isotopes for nuclear physics (GSI)
- Slow Extracted beams from traps
  - Low-energy antiproton beams for atomic collision physics

Antihydrogen and CPT Symmetry

Tests of particle – antiparticle symmetry properties



- Comparison misleading
- Inconsistent definition of figure of merit
  - Different denominators used
- Kaon case
  - Theory-dependent analysis
  - Possible CPT violating interaction constrained only to 10 % (Kobayashi & Sanda, PRL 69, 3139 (1992))
- Kostelecky et al.:
  - 1S-2S *insensitive* in 1st order
- Pattern of CPT violation is completely unknown
  - ➔ All sectors should be tested

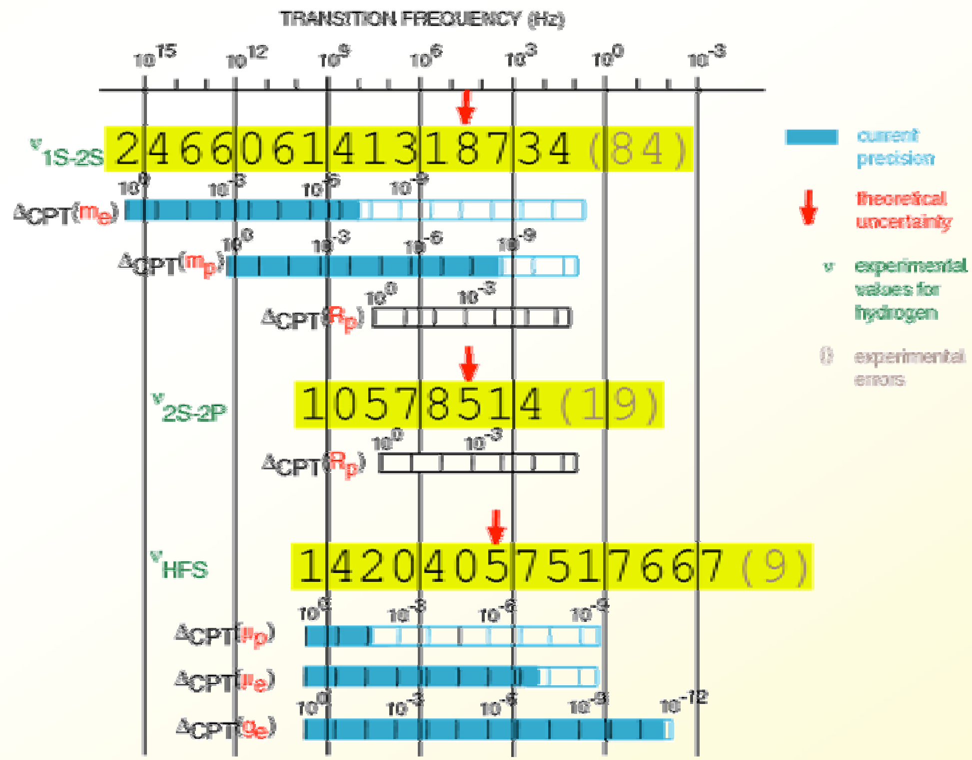
Ground-State Hyperfine Structure of (Anti)Hydrogen

- Leading term: Fermi contact term

$$\nu_{HF} = \frac{16}{3}\left(\frac{M_p}{M_p + m_e}\right)^3 \frac{m_e}{M_p}\frac{\mu_p}{\mu_N}\alpha^2 Ry$$

- a measurement of ν_{HF} will directly give a value for the magnetic moment of pbar
  - only known to 3 x 10^{-3}
- 1S-2S laser transition
  - Energy separation dominated by positron mass
  - Antiproton mass enters on 10^{-4} level via reduced mass
  - Primary CPT test in lepton sector

Comparison of experimental accuracies and CPT tests with hydrogen

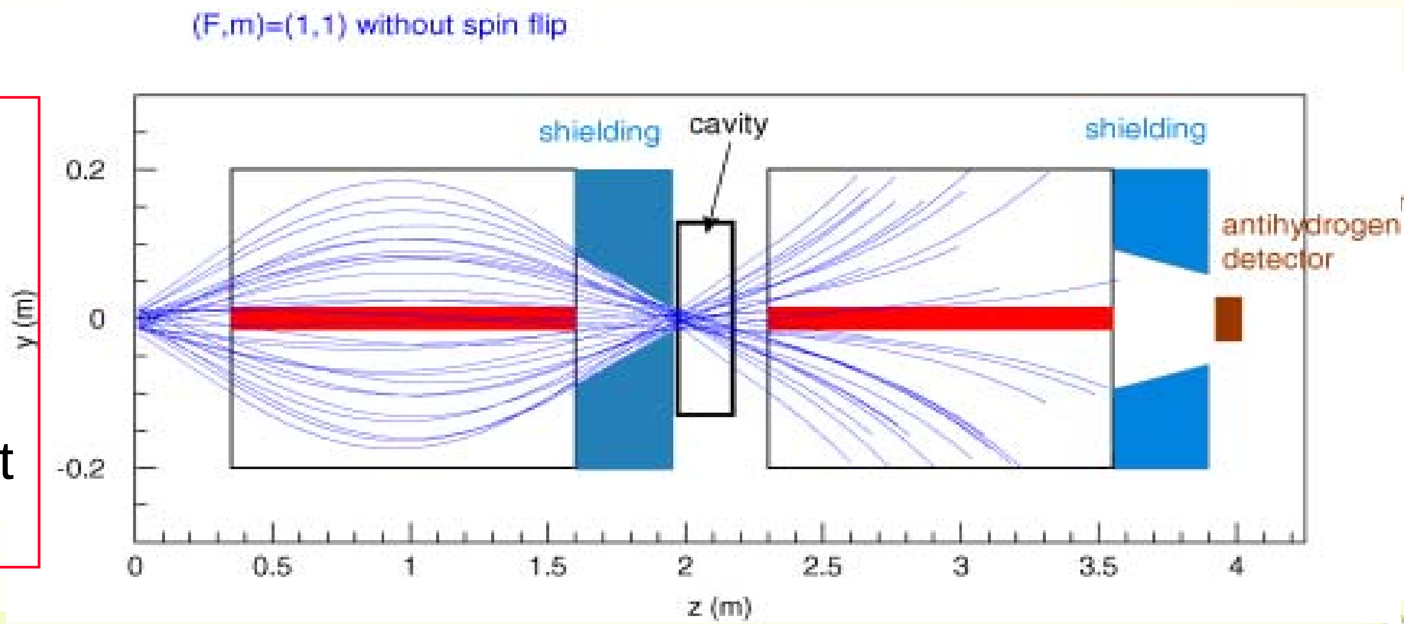


GS-HFS also contains information on form factors (structure) of (anti)proton!

HFS Measurement in Atomic Beam

- Production in nested Penning traps
- Hbar evaporate with 15 K into 4 p
- Spin selection and analysis by sextupole magnets
- Spin flip by microwaves

- S1 focussing for (F,m)=(1,1), (0,0)
- S2 rotated by 180 degrees
  - m=1 -> -1: defocusing
- atoms w/o spin flip blocked in S2
- microwave cavity between S1,S2
  - spin-flip -> S2 focuses

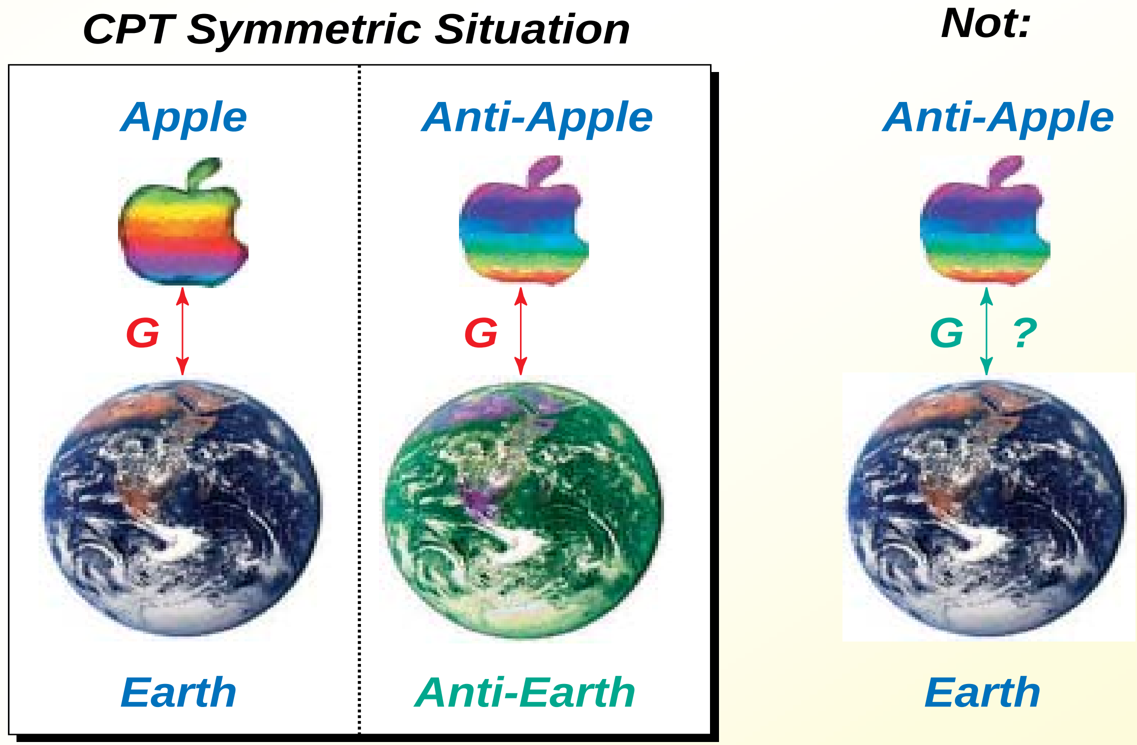


Achievable resolution
Line width 10–6
Rates
200 Hbar/sec yield
1 event per 2 minutes
Feasible with RFQD but higher rate favourable

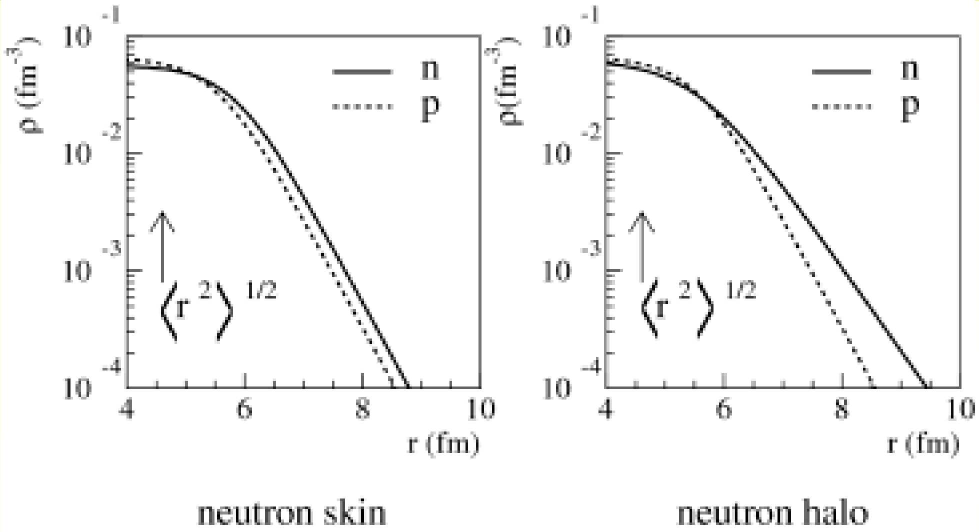
Gravitational Acceleration of Antimatter

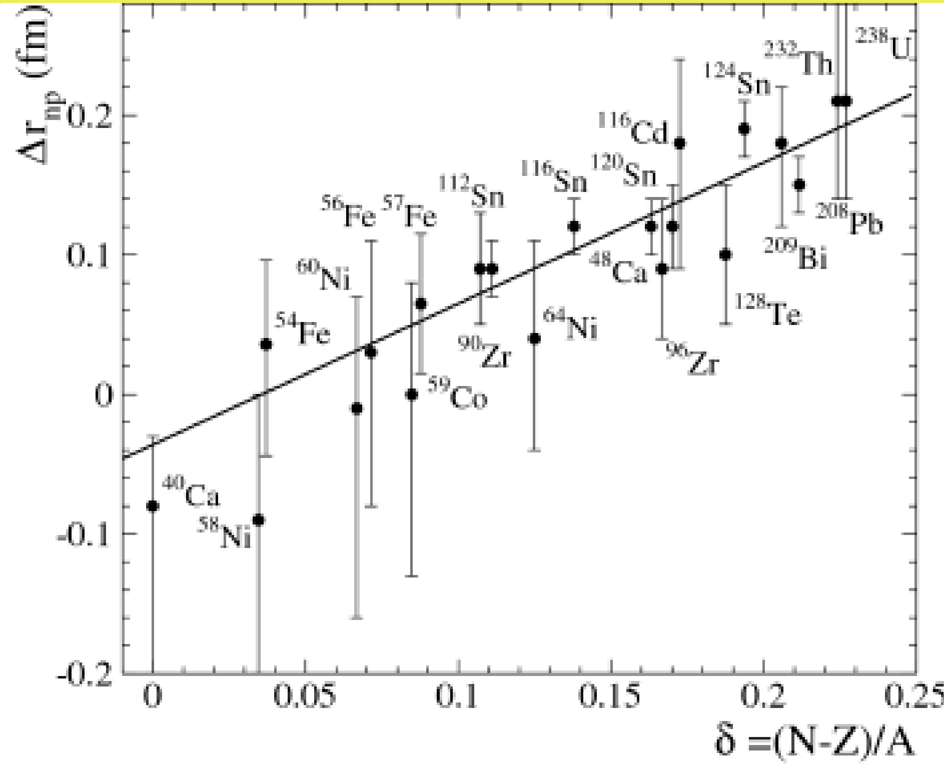
- No direct test of CPT
- Weak equivalence principle

- Highest precision reachable with neutral antimatter
- See poster by J. Walz
  - Ultra-cold antihydrogen atoms (μK) from neutral atom traps



Investigation of Nuclear Periphery With Antiprotonic Atoms (PS209 @ LEAR)





$p^- + {}^{Z}A \rightarrow {}^{Z}(A-1)$ annihilation with n

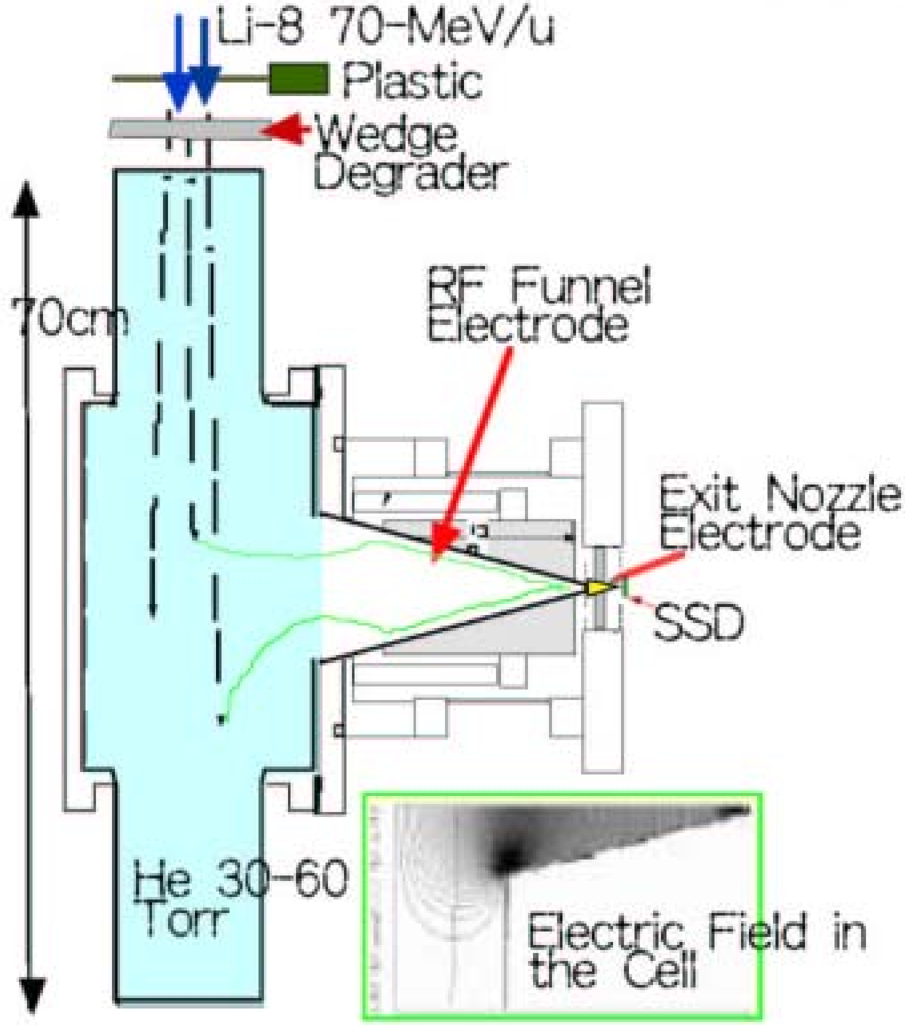
$p^- + {}^{Z}A \rightarrow {}^{Z-1}(A-1)$ annihilation with p

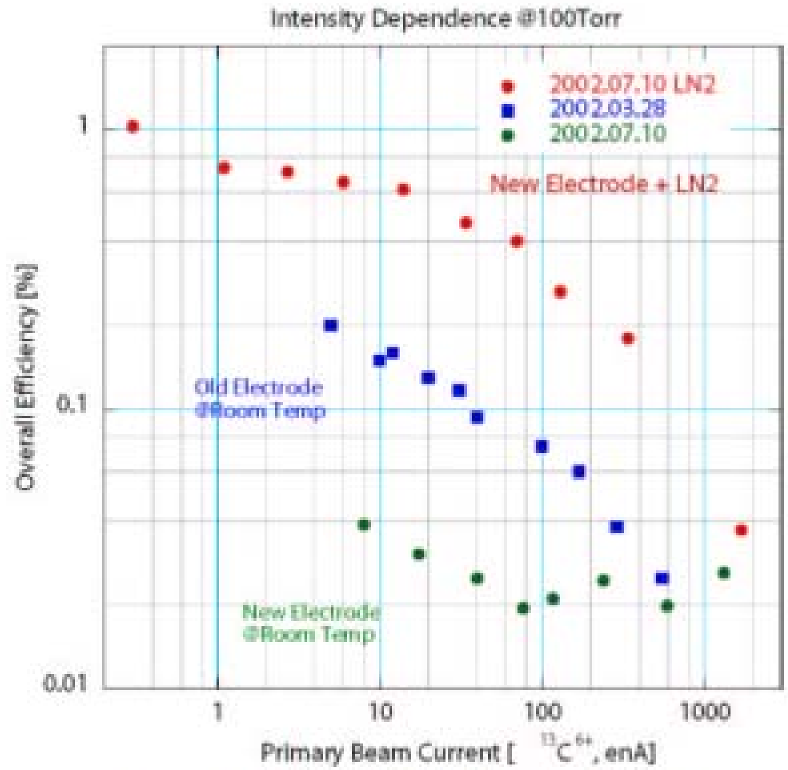
- Measurement of neutron halo parameters
  - Neutron diffuseness increases with neutron excess
- Extension to unstable nuclei interesting
  - Capture pbar, RI in trap, detect daughter nuclei

Availability of RI and pbar: GSI

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

Additional Key Technology: RF Ion Guide
-- Production of Slow RI Beam



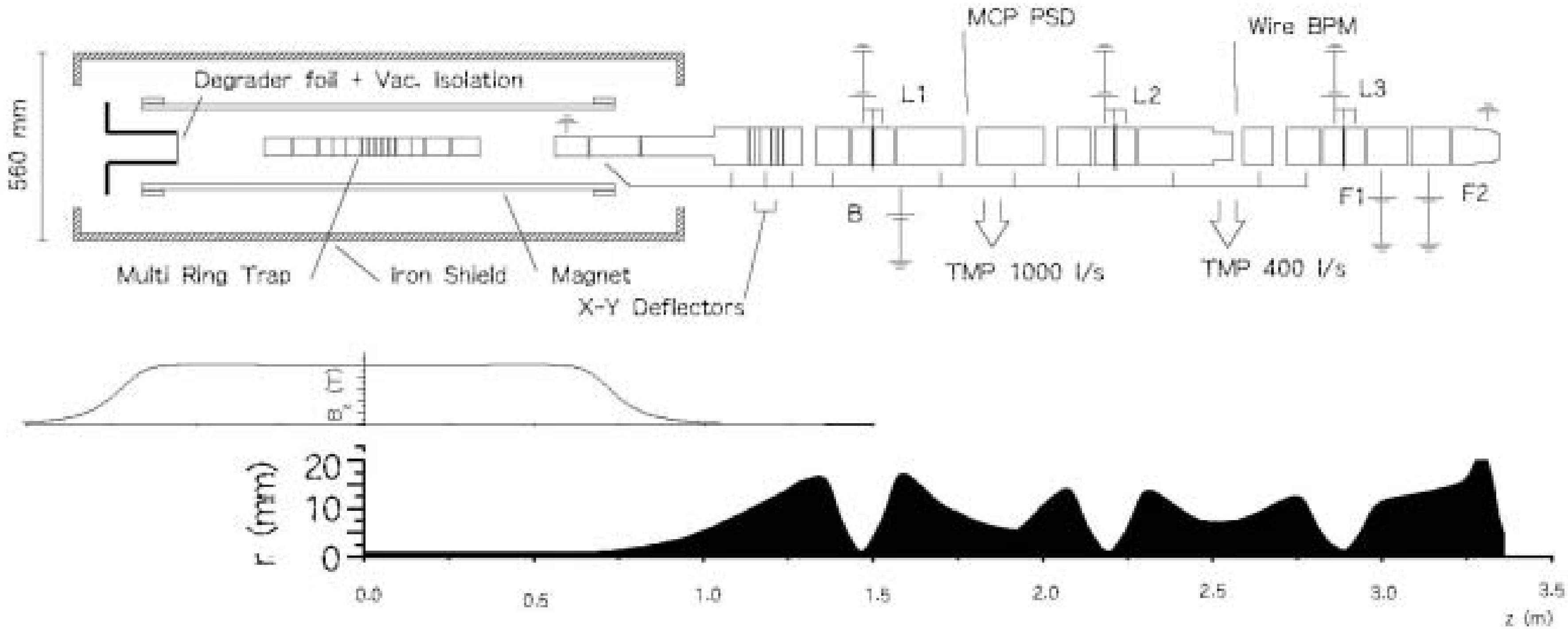


Efficiency of 1% Reached! (02/9/19)

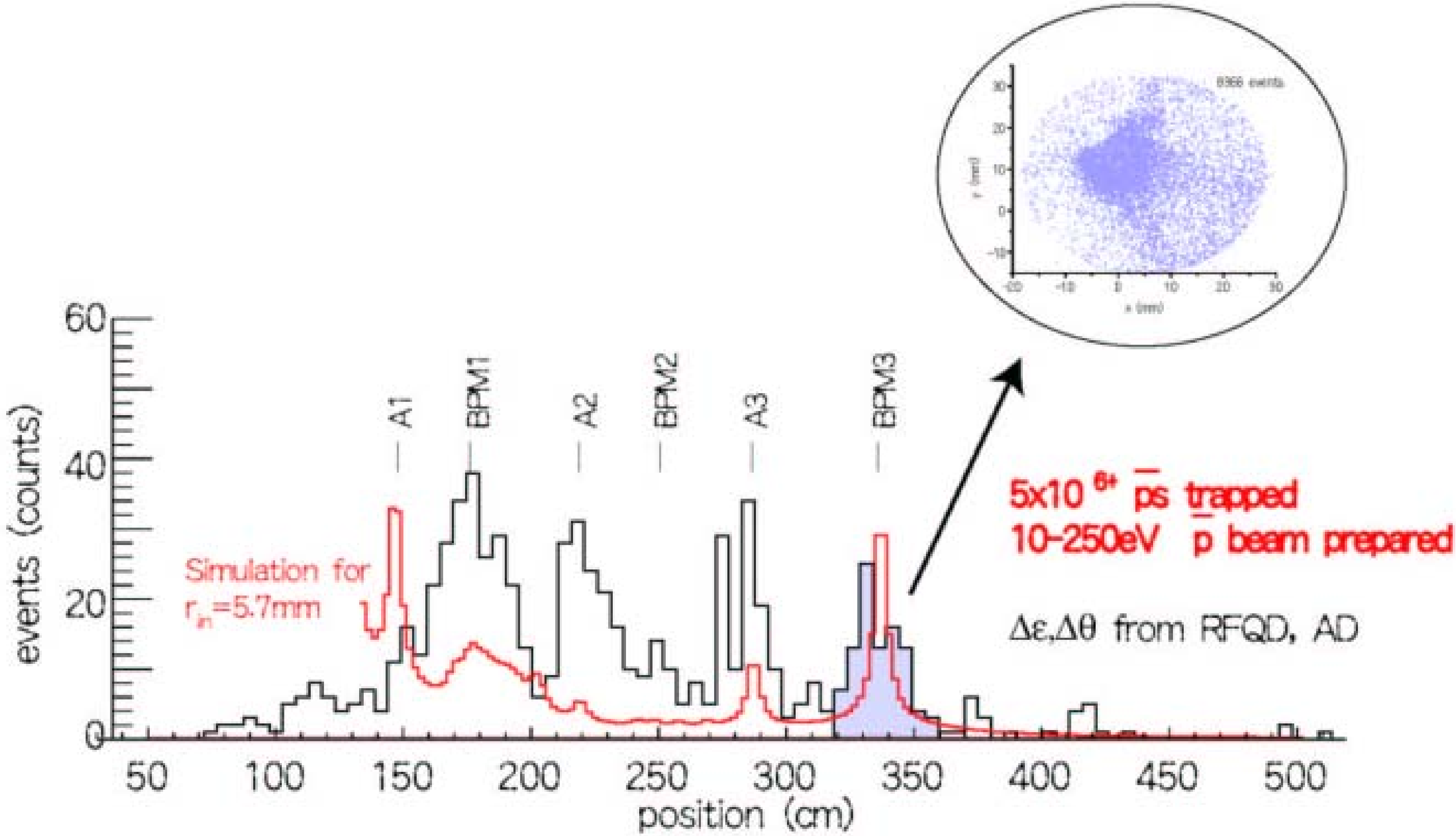
Wada et al.

Transport Beam Line

High transport efficiency extracted from high B field
Effective differential pumping (10^{-12} Torr 10^{-6} Torr)

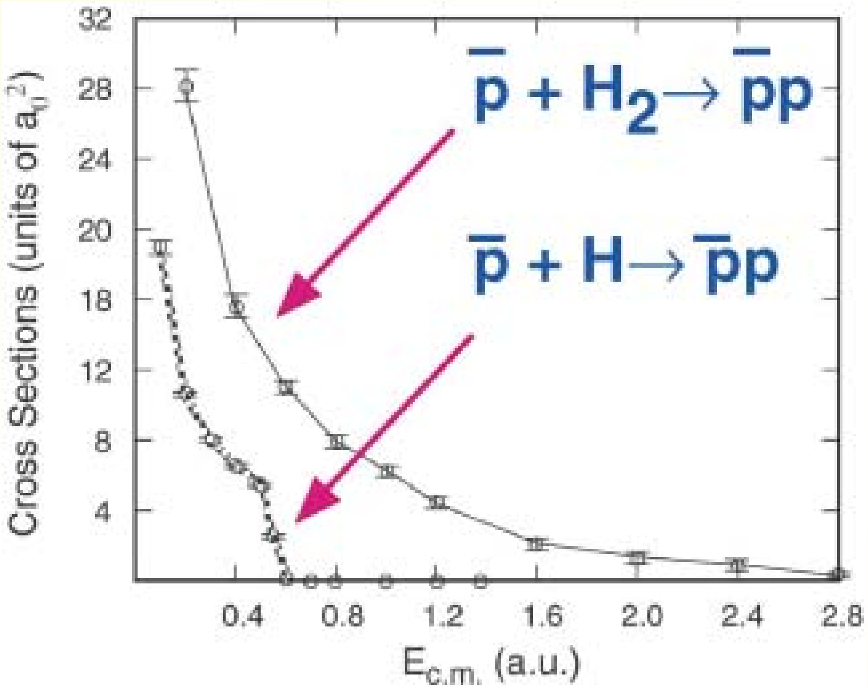


Extraction of Ultra Slow $\bar{p}$ Beam (10-250eV)

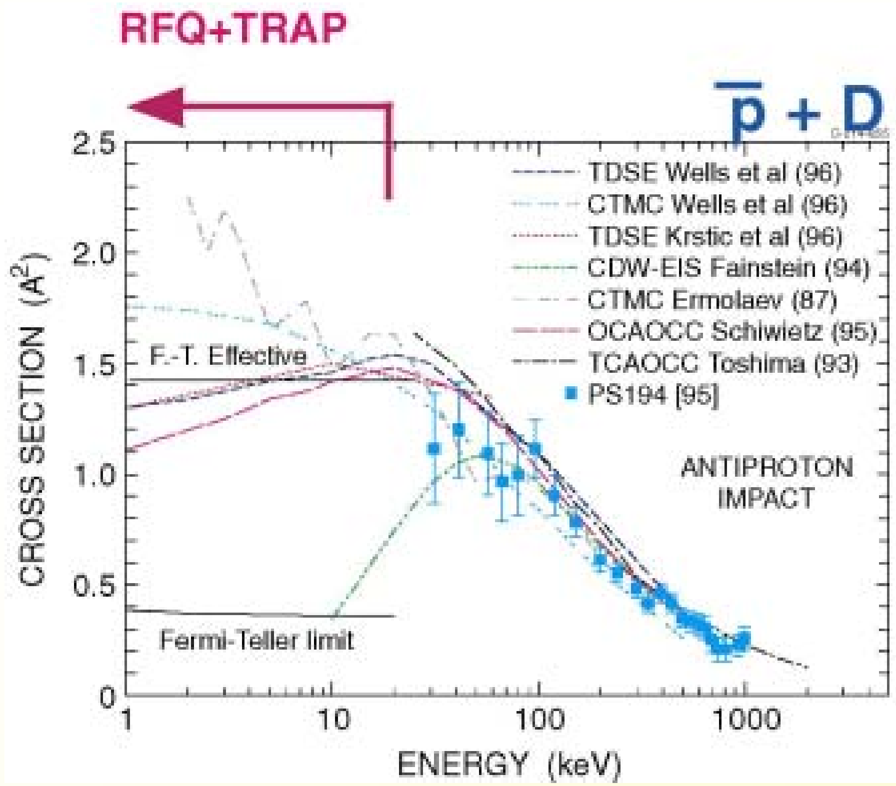


Physics with extracted Antiprotons: 10 – 1000 eV

- Formation of antiprotonic atoms (protonium, ...)

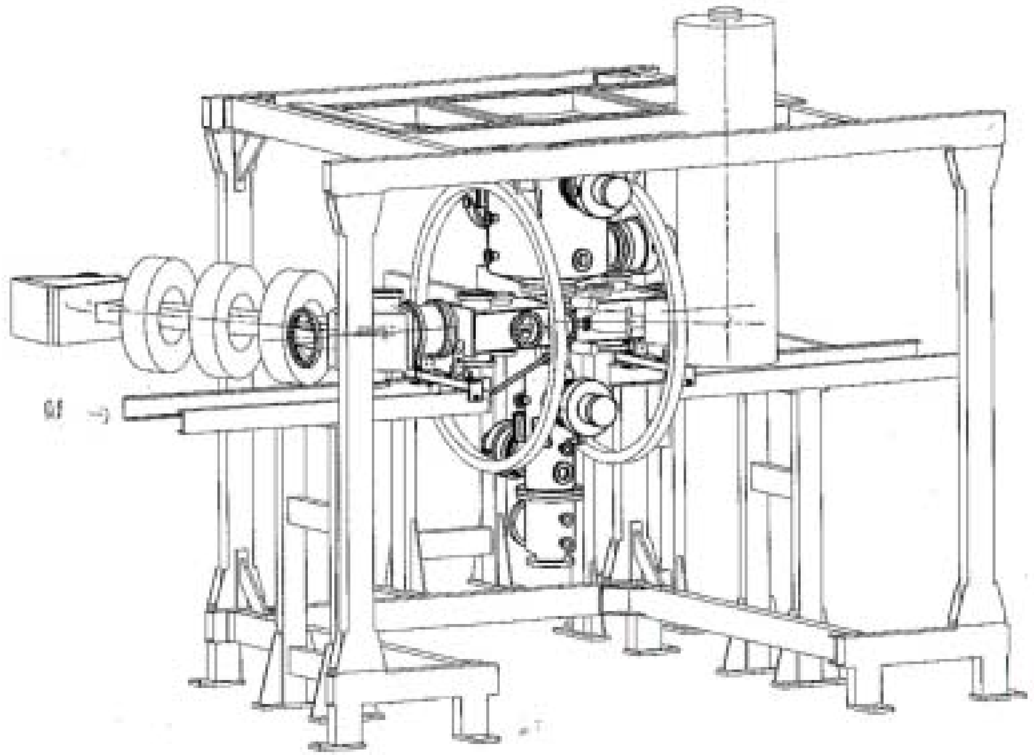


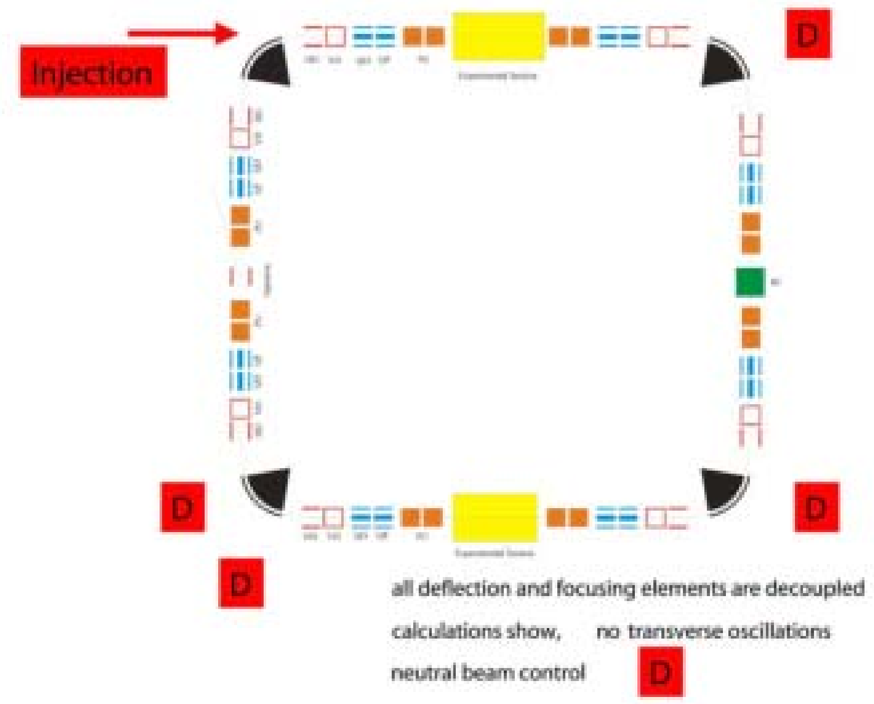
- Ionization in single collision by slow antiprotons



Extracted Antiprotons for Collision Experiments

- Reaction Microscope for fully differential collision measurements
- Table-top electrostatic storage ring

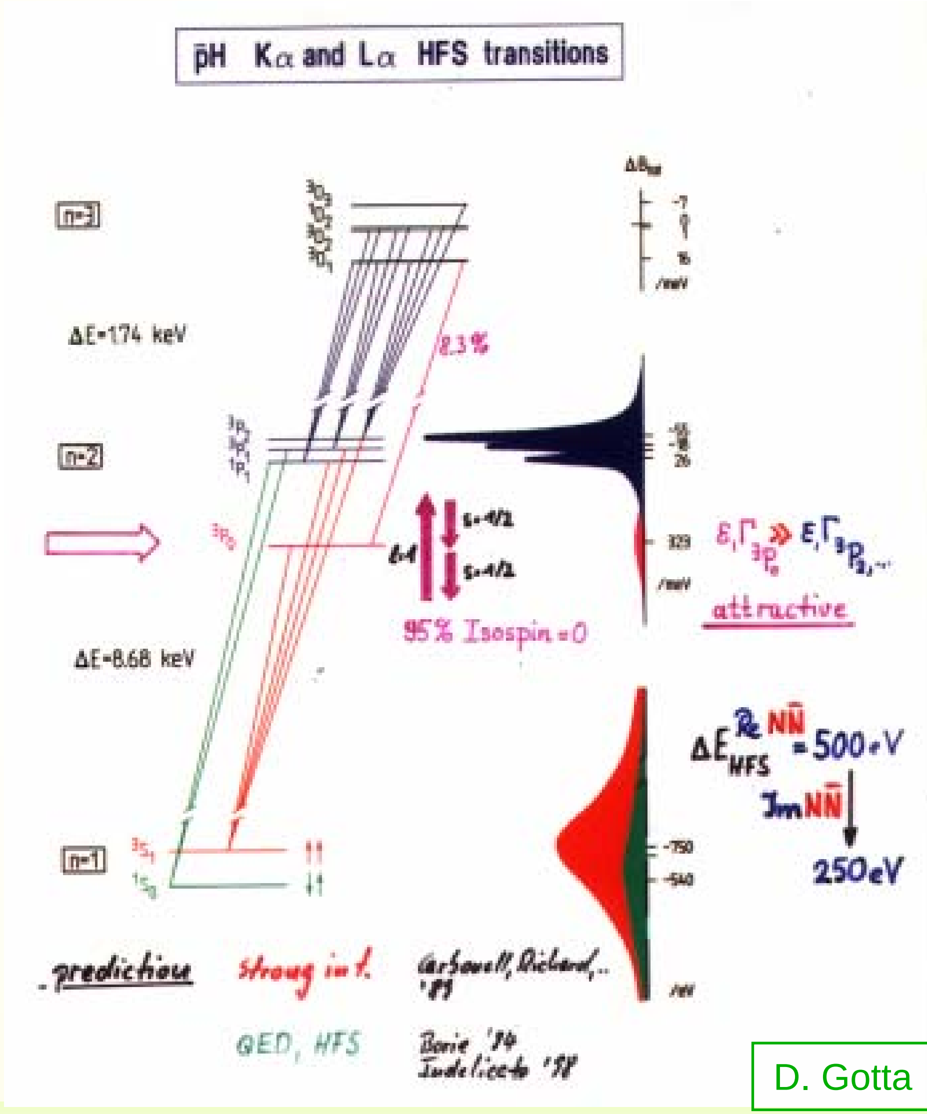




J. Ullrich, H Schmidt-Böcking

Slow extracted antiproton beams

- Many experiments require DC beam
  - X-Ray measurements of protonium and other protonic atoms
  - talk by P. Indelicato
    - Strong interaction shift and width
    - Bound state QED
    - Crystal spectrometer (small solid angle) needs high rate
- Few MeV slow extraction like LEAR or
- Extraction from trap and post-acceleration
  - 100 keV beam
- ASACUSA was approached by two groups to provide slow extracted beams



D. Gotta

Summary and Outlook

- Low-energy antiprotons are important tools for
  - Tests of fundamental symmetries: Antihydrogen (CPT, gravitation)
  - Long-term experiments:
    - 2 years until first production of cold antihydrogen
    - Longer time for precision spectroscopy
- Future of the AD uncertain
- High Intensity available at GSI & HITRAP advantageous for
- Availability for slow extracted beams advantageous for certain type of experiments
  - Slow extraction from trap may be o.k.
- Simultaneous Availability of Antiprotons and Radioactive Beams open possibilities for systematic studies of neutron distributions

ASACUSA collaboration @ CERN-AD

Asakusa Kannon Temple
by Utagawa Hiroshige (1797-1858)

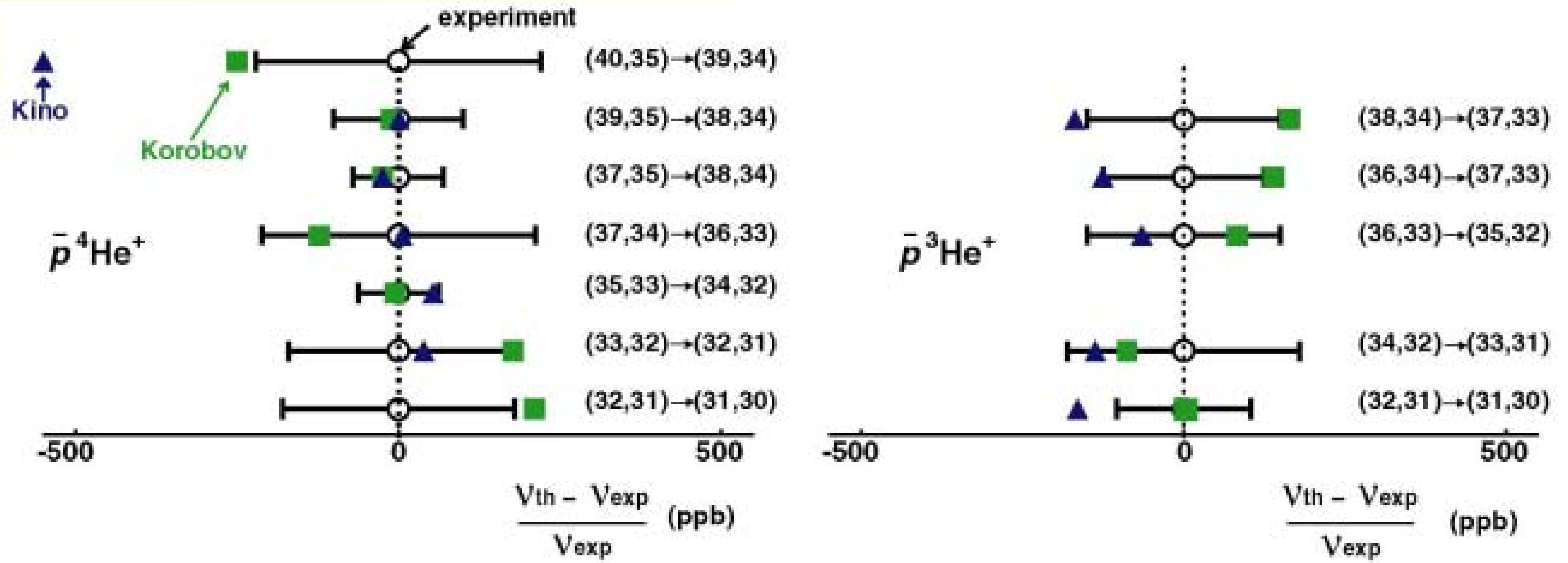
Atomic Spectroscopy And Collisions Using Slow Antiprotons

- University of Tokyo, Japan
- RIKEN, Saitama, Japan
- Tokyo Institute of Technology, Japan
- University of Tsukuba, Japan
- Institute for Molecular Science, Okazaki, Japan
- Tokyo Metropolitan University, Japan
- CERN, Switzerland
- University of Aarhus, Denmark
- University of Wales Swansea, UK
- KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- University of Debrecen, Hungary
- KVI, Groningen, The Netherlands
- PSI Villigen, Switzerland
- Ciril -Lab. Mixte CEA-CNRS, Caen Cedex, France
- GSI, Darmstadt, Germany
- Institut für Kernphysik, Iniversität Frankfurt
- Universität Freiburg, Germany
- St. Patrick's College, Maynooth, Ireland
- The Queen's University of Belfast, Ireland

~ 40 members

Spokesman: R.S. Hayano, University of Tokyo

Comparison to theory: RFQD data 2002



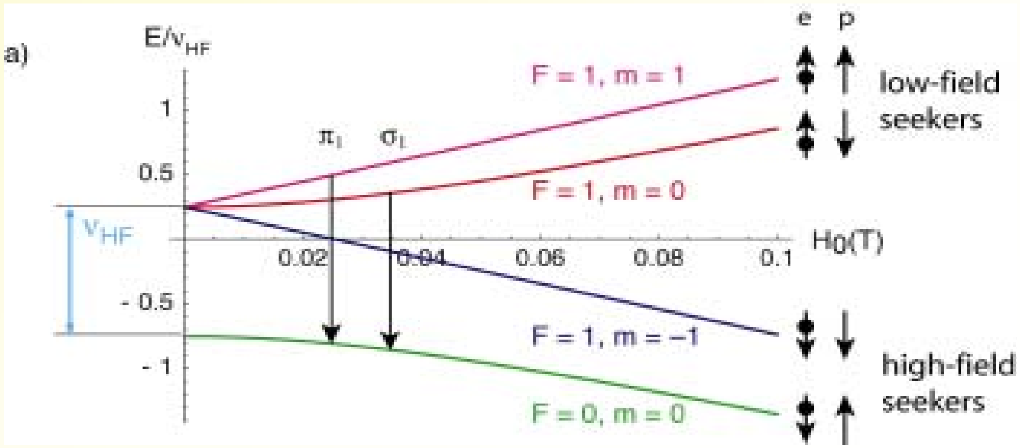
- Only data taken with RFQD at density 5×10^{17} cm^{-3} (factor 1000 lower than ever)
- Data free from systematic error from extrapolation to zero density
- Good agreement for most states except 1
  - Problems for calculations for high-n, low-l states?

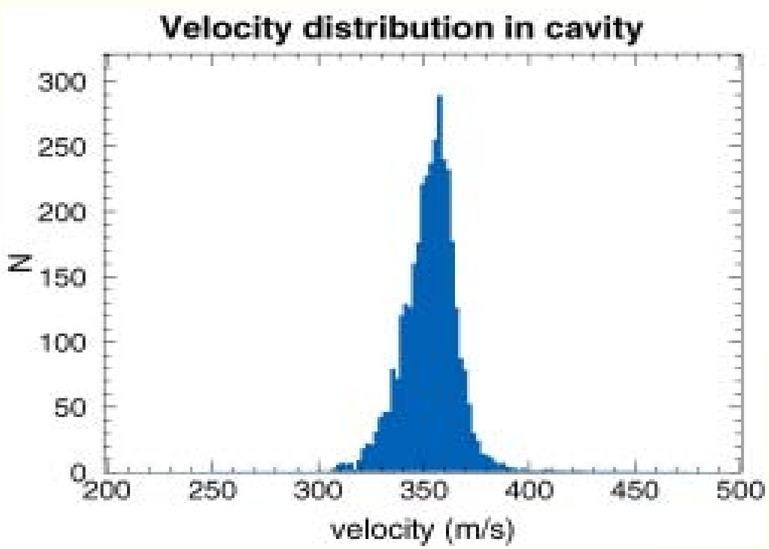
Experimental accuracy:

8×10^{-8}

PRELIMINARY

Achievable Resolution





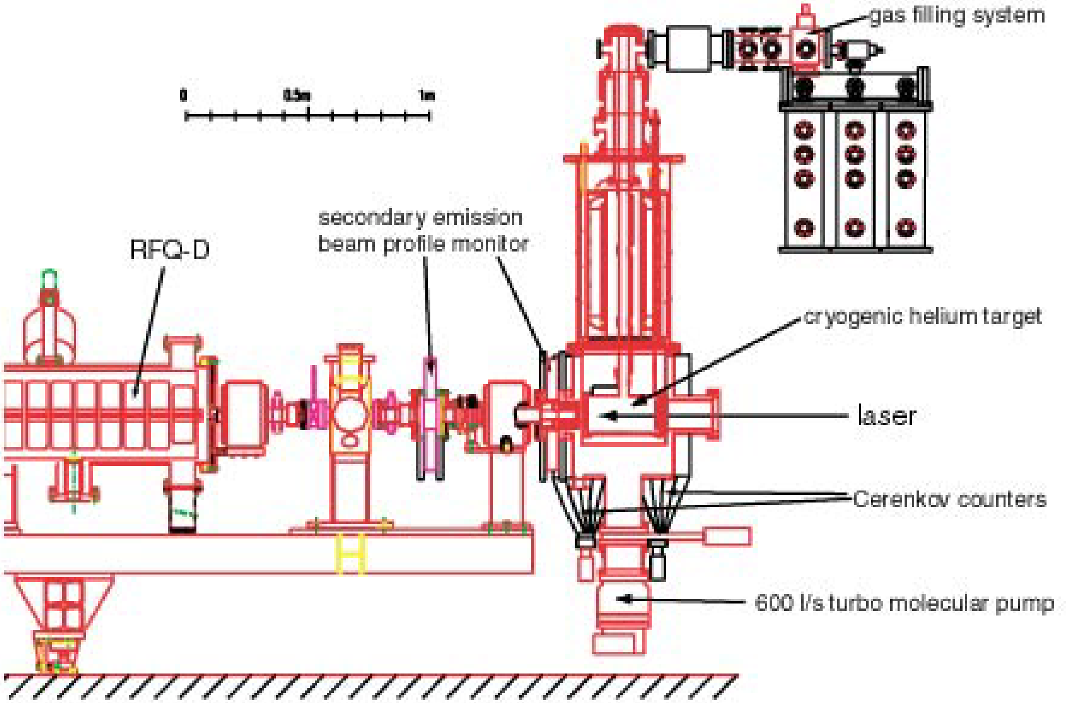
Micro-wave induced transition

- Transitions in zero field
  - measure directly ν_{HF}
- Transition moment of the order of Bohr magnetron
- Velocity acceptance of double sextupole is rather narrow
- Possibility to induce π-pulse if cavity length and amplitude of oscillating field are adjusted:
- Typical values
  - $L = 10$ cm, $B_1 = 5\text{x}10^{-4}$ Gauss
- FWHM of resonance curve:

$$\delta\nu \sim 2 - 3 \text{ kHz}: \delta\nu / \nu \sim 2\text{x}10^{-6}$$

- line can be split to higher precision

$\bar{p}He^+$ Laser Spectroscopy at Ultra-low Density: Radio Frequency Quadrupole Decelerator: 20-120 keV



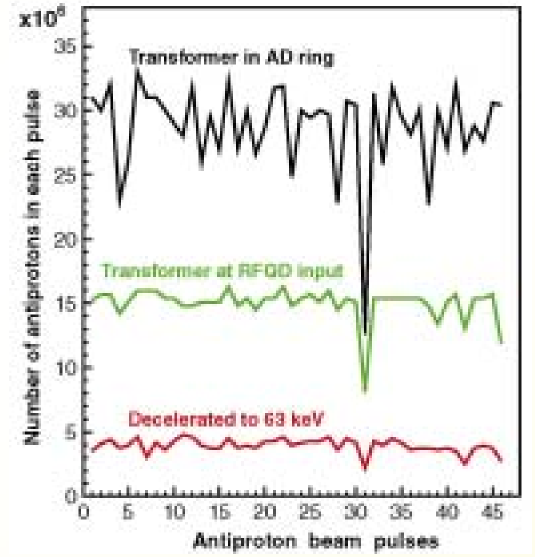
- RFQD: 5.3 MeV -> 20 – 120 keV (eff.~25%)
- Differential pumping + ultra-thin beam window (~ 1 µm Mylar)
- high efficiency of stopping antiprotons at ultra-low densities (p < 1 mbar, T~20 K)

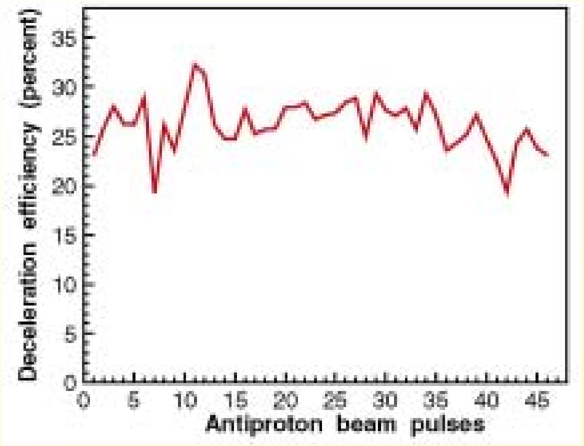
AD & Experiments

RFQD Performance

- Simulated deceleration efficiency ~40%
- Measurement by
  - Separation 5 MeV / 63 keV components by dipole magnet
  - Intensity of incoming beam by calibrated transformer
  - 63 keV component absolutely determined by activation of Al plates

    - Al ->





HFS and theory, CPT

- Fermi contact term in agreement with experimental value by about 32 ppm
- higher-order corrections
  - Zeemach corrections
  - depend on magnetic *and* electric form factors of proton

$$\Delta\nu_{\mathrm{Zemach}} = \frac{2Z\alpha m_e}{\pi^2} \int \frac{d^3p}{p^4} \left[\frac{G_E(p^2)G_M(p^2)}{1+\kappa} - 1 \right]$$

  - Zeemach corrections

    ~ - 41.1(7) ppm
  - remaining discrepancy (incl. Polarizability)

$$\frac{\nu_{\exp} - \nu_{th}}{\nu_{\exp}} \approx 3.5 \pm 0.9 \text{ ppm}$$

- Comparison of experimental accuracies and CPT tests with hydrogen
- GS-HFS also contains information on form factors (structure) of (anti)proton!

Trapping and Cooling of Antiprotons

Multi-Ring Trap (MRT)

Stable Storing
Large Volume

SC Solenoid

Quick B field scan
Cold bore
Bakable bore with magnet on
Movable bore for alignment