THE ALPHA COLLABORATION

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Motivations in Brief

•Tests of fundamental symmetries by applying ***precision*** atomic physics techniques to anti-atoms:

- •CPT violation?
- •Lorentz invariance violation?

Physics beyond the Standard Model?

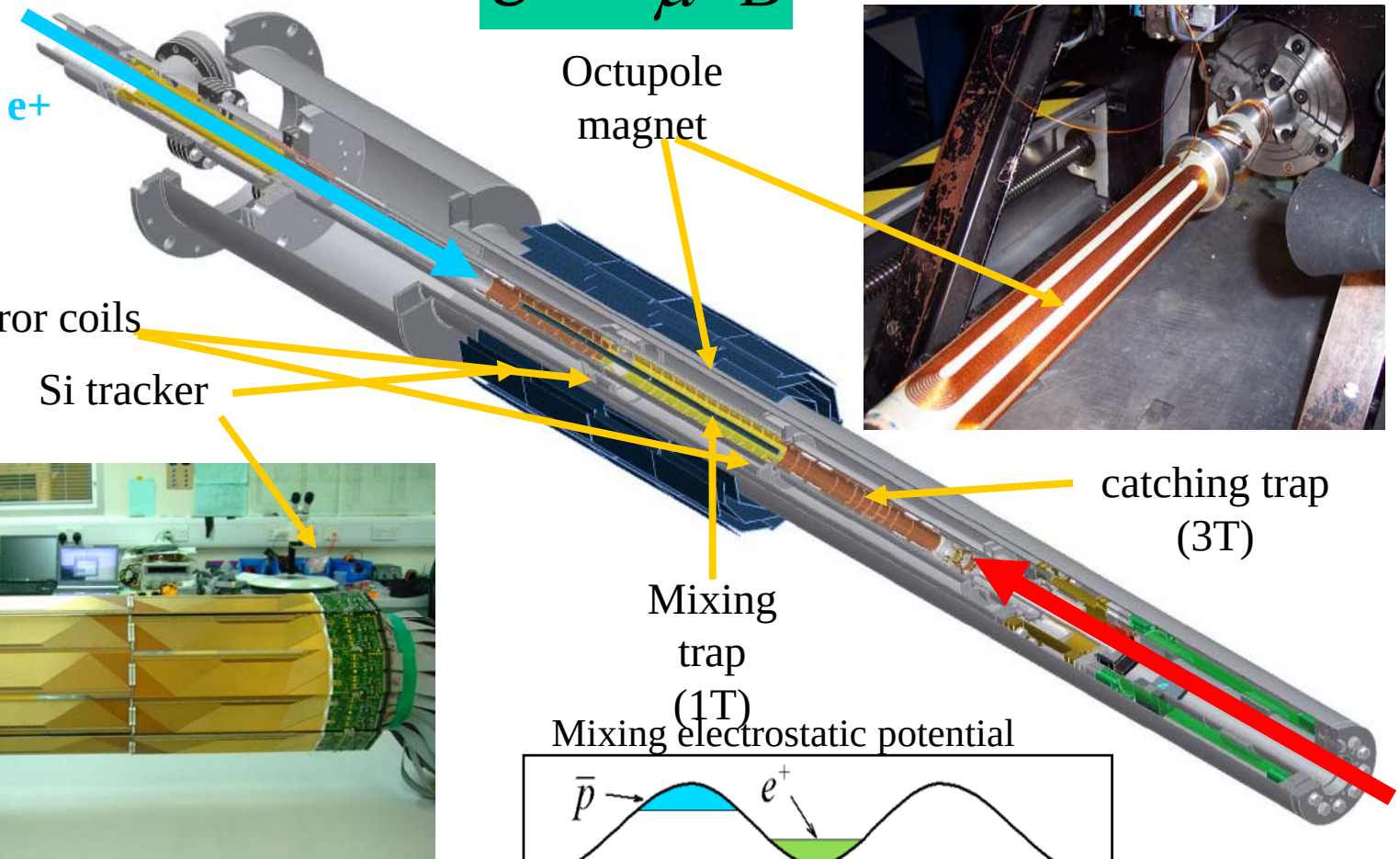
The initial physics goal of ALPHA is to TRAP antihydrogen atoms, so that they can be studied in detail.

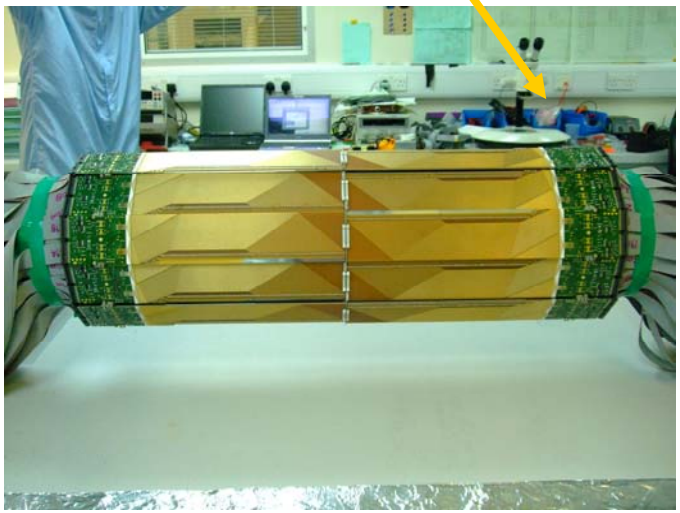
•(Anti)-Gravity - no current experimental effort in ALPHA, but success in ALPHA may be a prerequisite for this work

ALPHA Apparatus

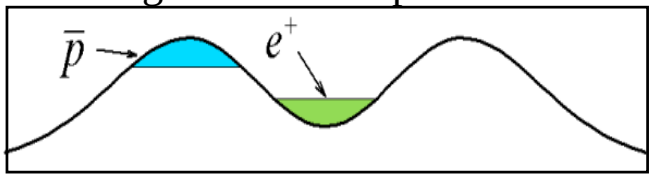
Superimpose Penning Trap and Magnetic Trap for Neutral Atoms

$$U = -\vec{\mu} \cdot \vec{B}$$





Mixing electrostatic potential

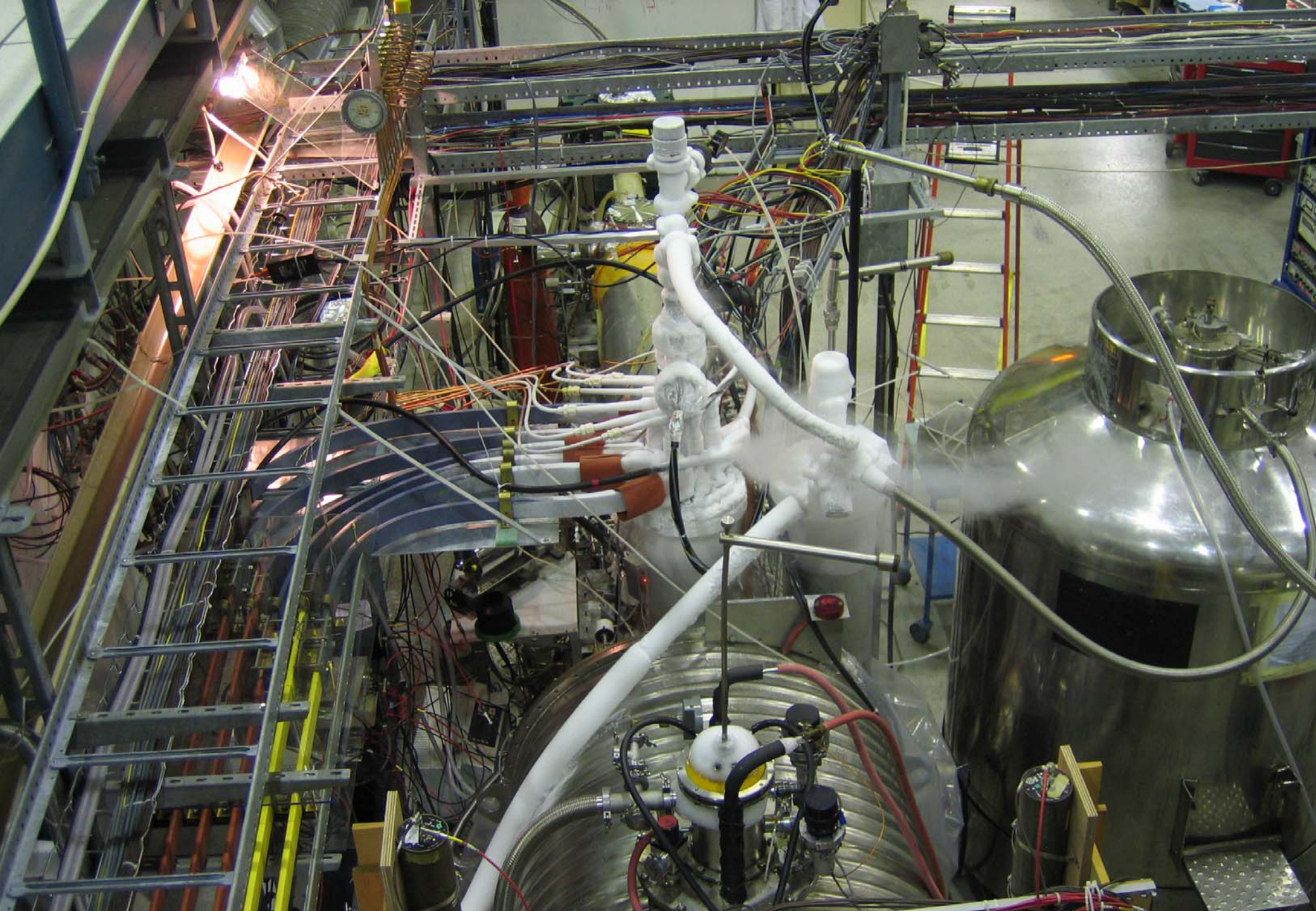


ALPHA in Brief:

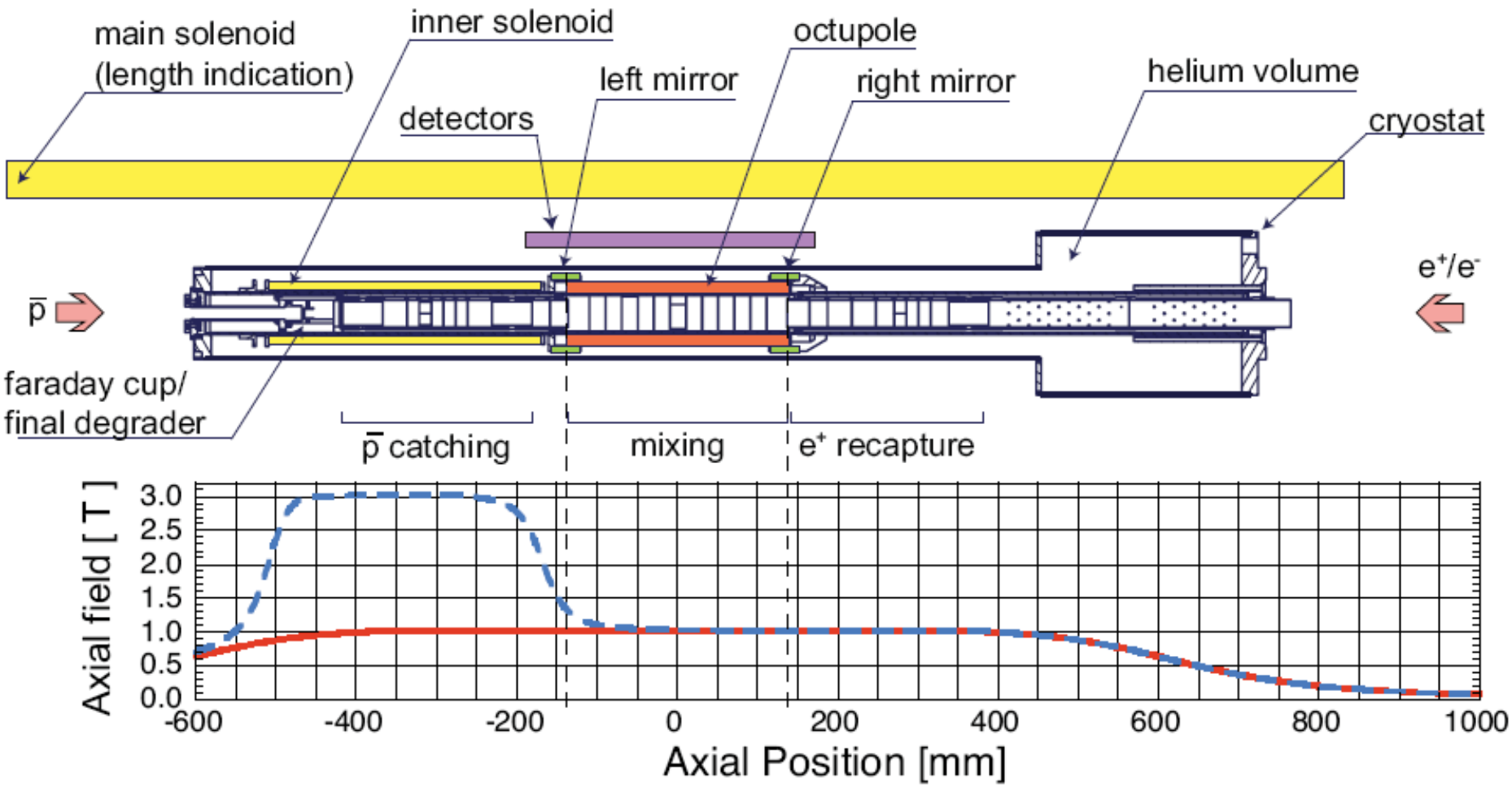
Initial physics goal: trapped antihydrogen

Long term physics goal: spectroscopic comparison of hydrogen and antihydrogen

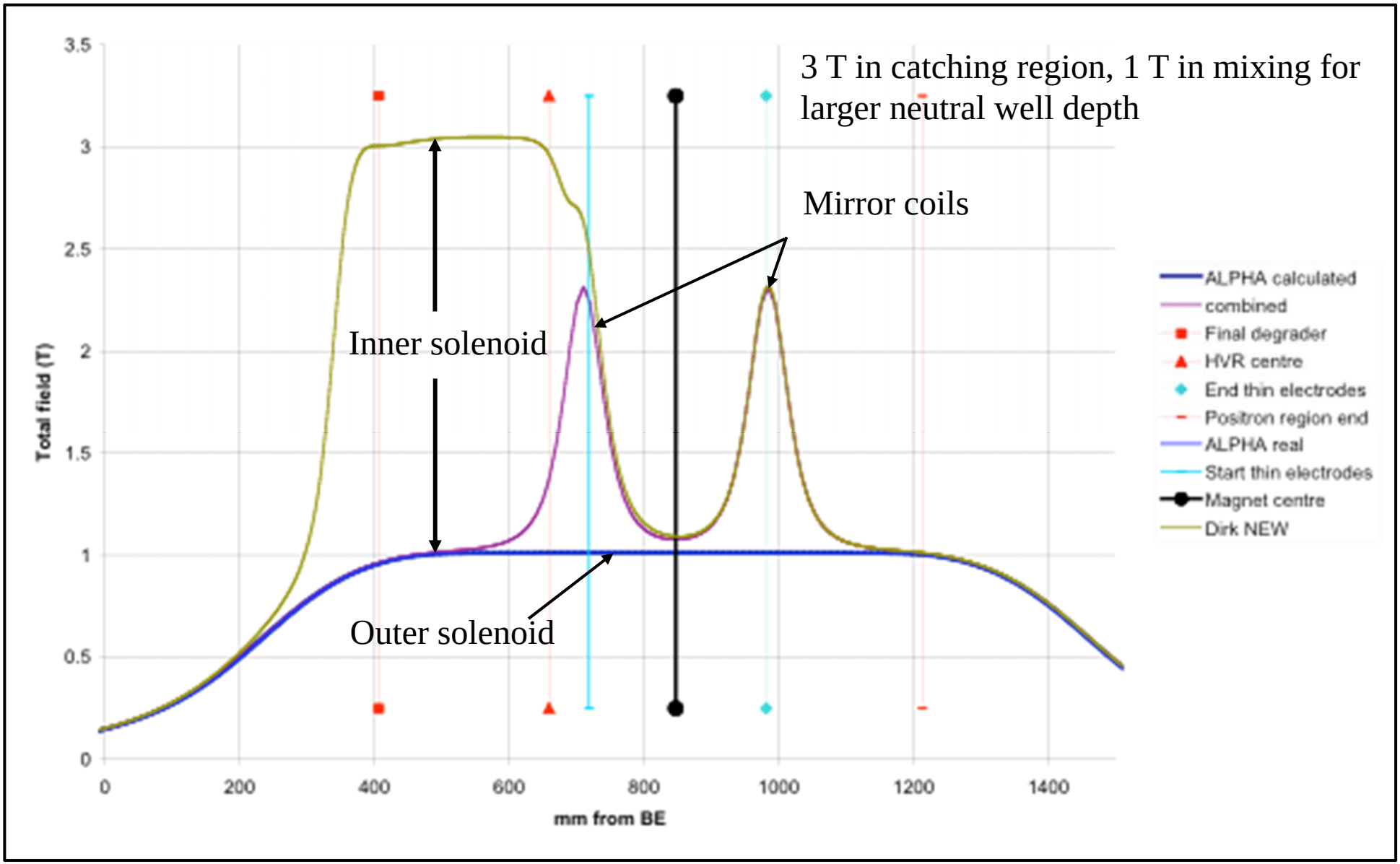
- Transverse multipole for trapping antihydrogen
- Higher order (octupole) to minimize plasma perturbations
- Longitudinal trapping by mirror coils
- Well depth of about 0.7 K at r = 23 mm
- Silicon vertex detector for spatial imaging of antiproton annihilations
- Special magnet construction to minimize scattering of pions
- Three layers of silicon - reconstruct track curvature
- First operation and commissioning 2006



ALPHA Schematic



Axial Field Configuration



Where do we stand?

- ALPHA device fully commissioned
- Demonstrated compatibility of charged plasmas and multipole trap
- Demonstrated antihydrogen production in octupole trap; correlated field ionization with detector triggers
- Developed necessary diagnostics for optimizing trapping experiments
- Fast shutdown (ms) of magnetic trap for detection of trapped antihydrogen
- First systematic search for trapped antihydrogen (2008)
- No trapping signal yet, steep learning curve

Vertex Detection - 2008

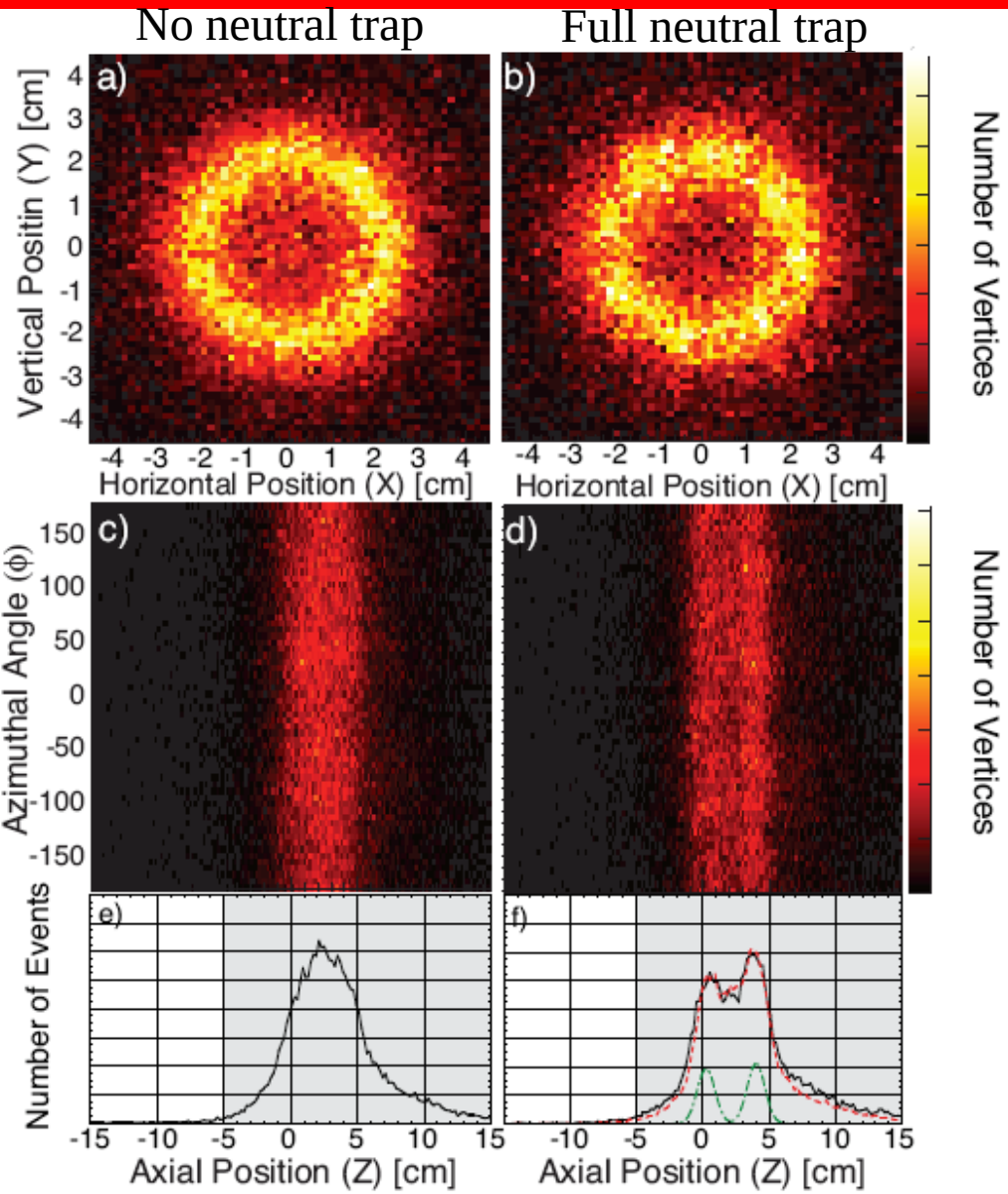


FIG. 3: (a-b) Transverse cross sections of the $\bar{p}$ annihilation vertex distributions during mixing with (a) no trap and (b) full neutral trap. (c-d) Corresponding z-ϕ distributions. (e-f) Corresponding axial (z) distributions. (f) Dashed (red): Fit to distribution, see text; Dot-dashed (green) peaks in fit. The shaded area marks the three layer part of the detector used for tracking. Left of this area the detector has only one layer of silicon. The slight asymmetry in the axial distributions (in particular the tails) is due to the lower reconstruction efficiency outside the three layer section. For clarity the plots have been normalized to have the same total number of events.

Antihydrogen Production in Neutral Trap

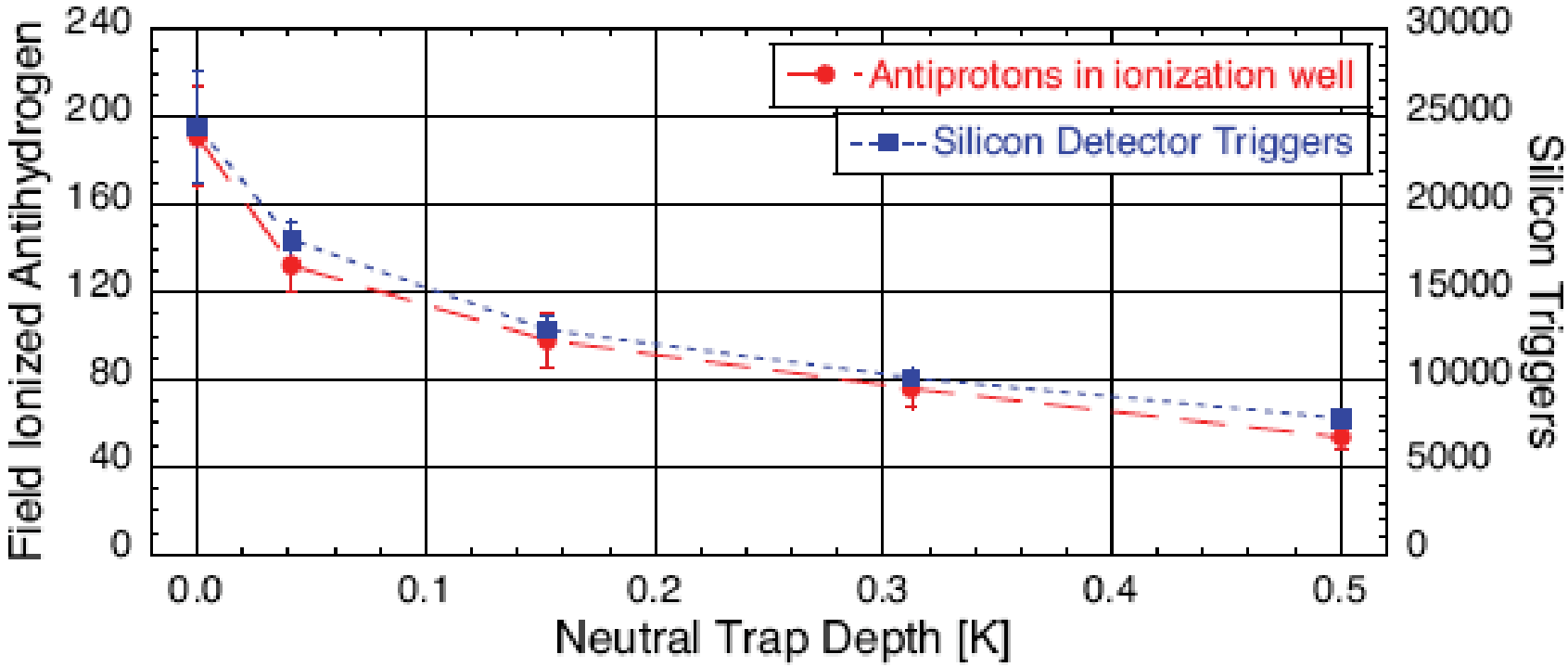
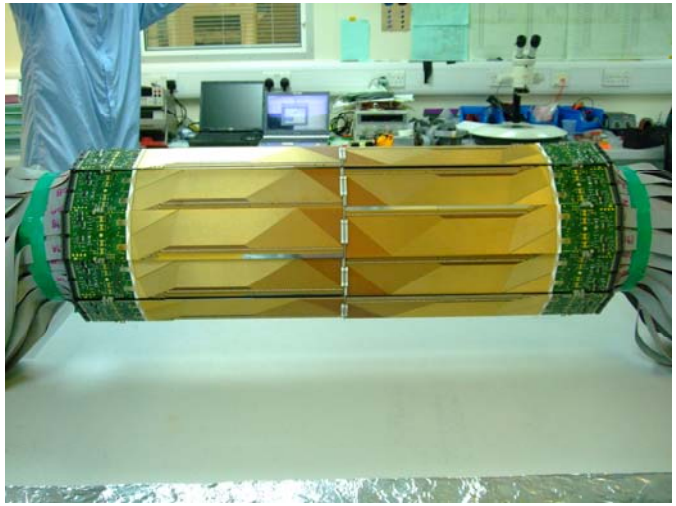


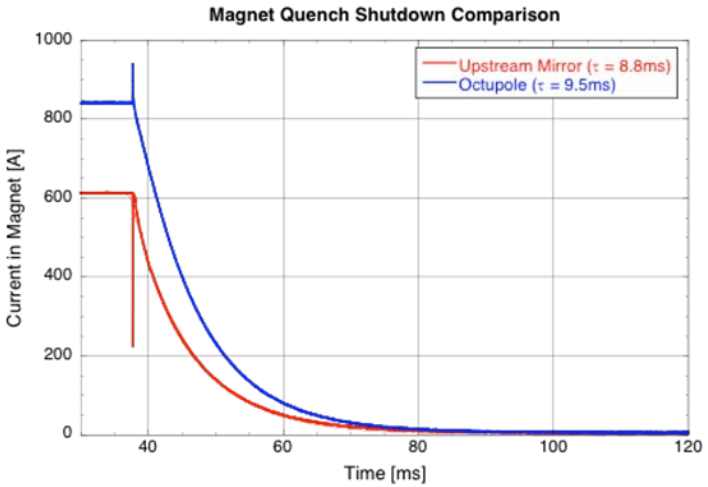
FIG. 2: Number of field-ionized $\bar{H}$ and detector triggers as a function of the depth of the neutral trap for ground state $\bar{H}$. The uncertainties represent variations in reproducibility. The values are normalized to 10^5 $\bar{p}$'s brought into mixing.

Detection of Trapped Antihydrogen

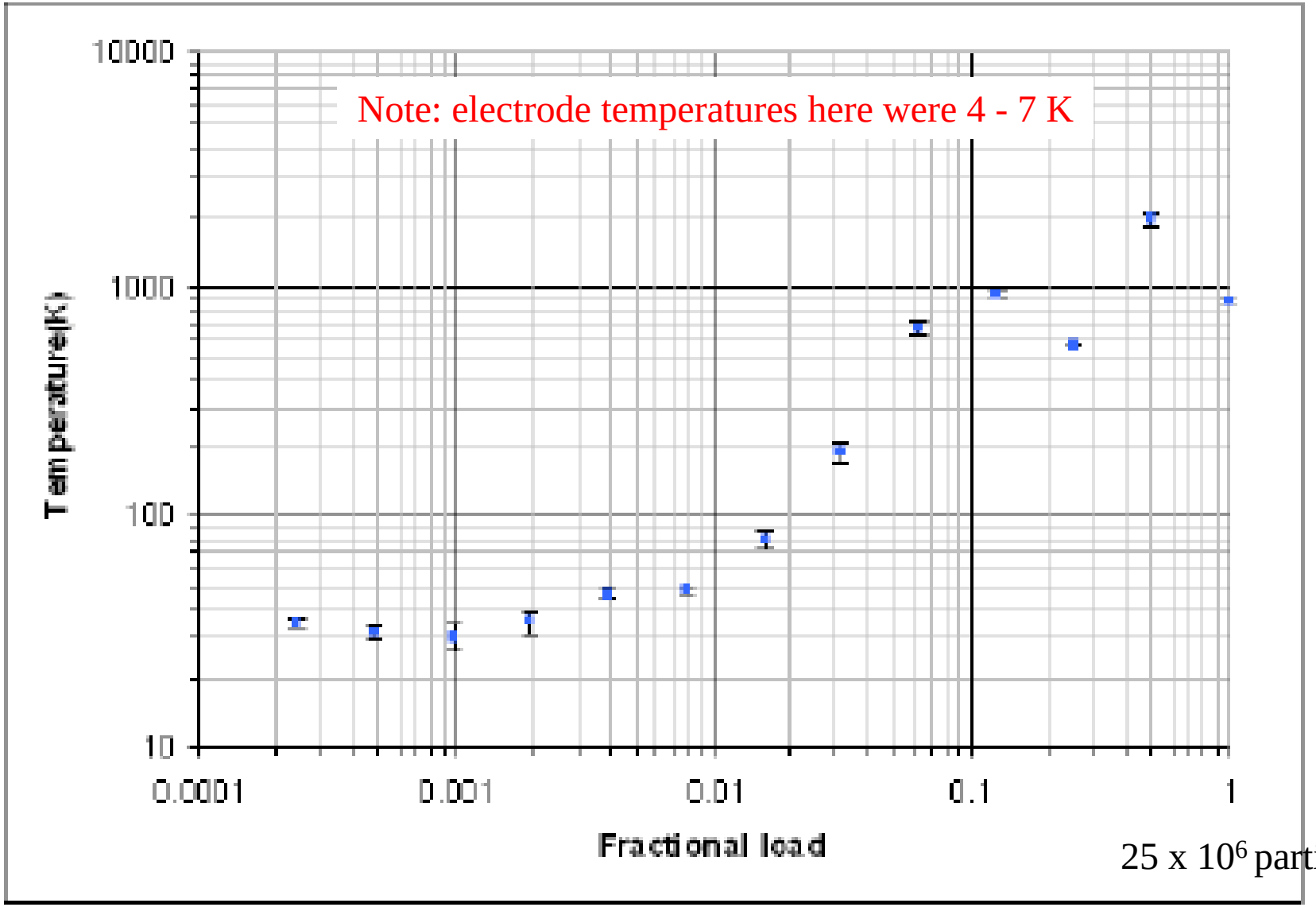
- **Trapped Hbar detection**:
  - Create Hbars in a neutral trap
  - Clear all the charged particles
  - Release the trap in ~20 msec
  - Look for pbar annihilations on the walls
- First measurements are statistics limited
- Need best event characterizations, background rejections
- → Position sensitive detection of antihydrogen annihilations
- 3D annihilation imaging: unique tool to study plasmas



Si: 3 layers



Example Electron T Measurement

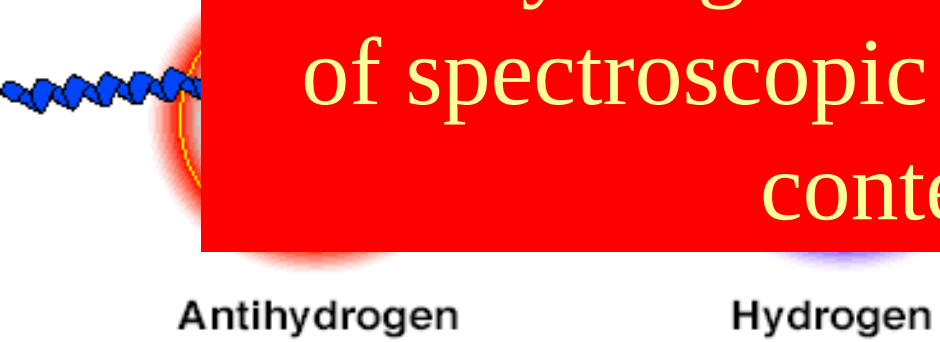


25 x 10^6 particles

Still The Dream – 1S-2S Spectroscopy

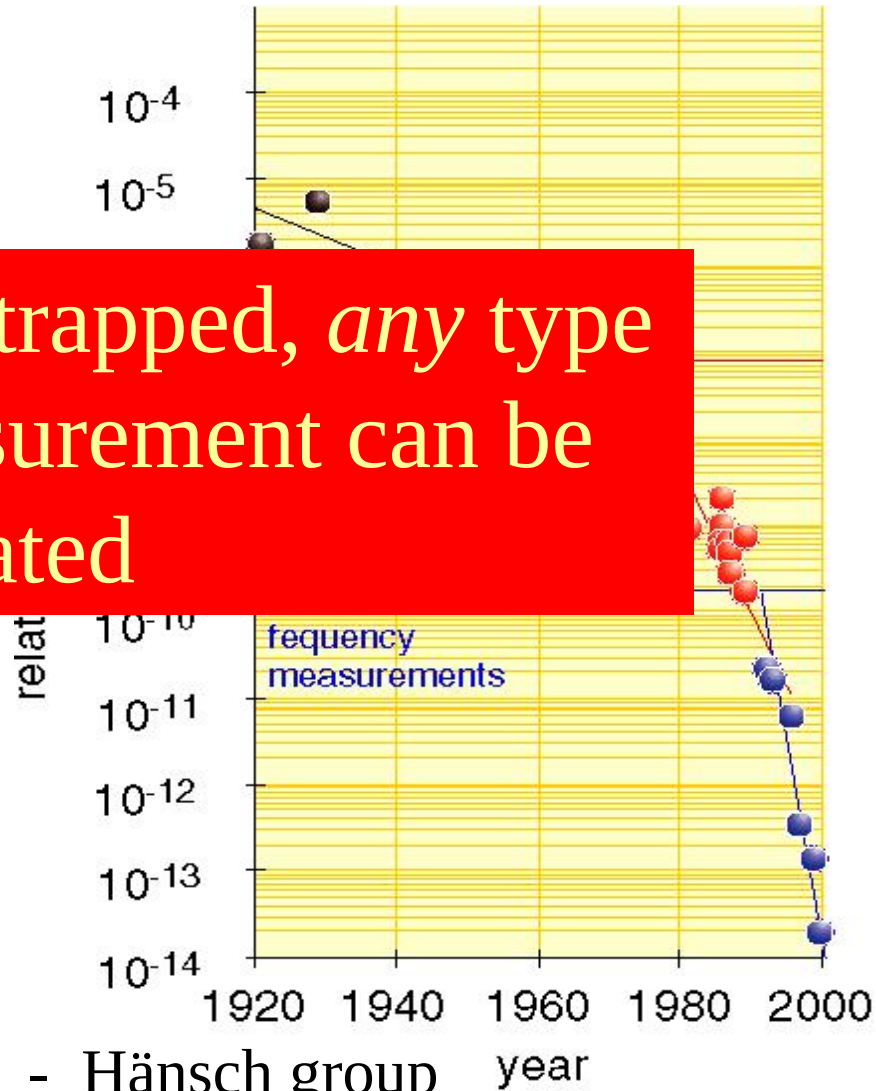
1s-2s two-photon spectroscopy

If antihydrogen can be trapped, *any* type of spectroscopic measurement can be contemplated



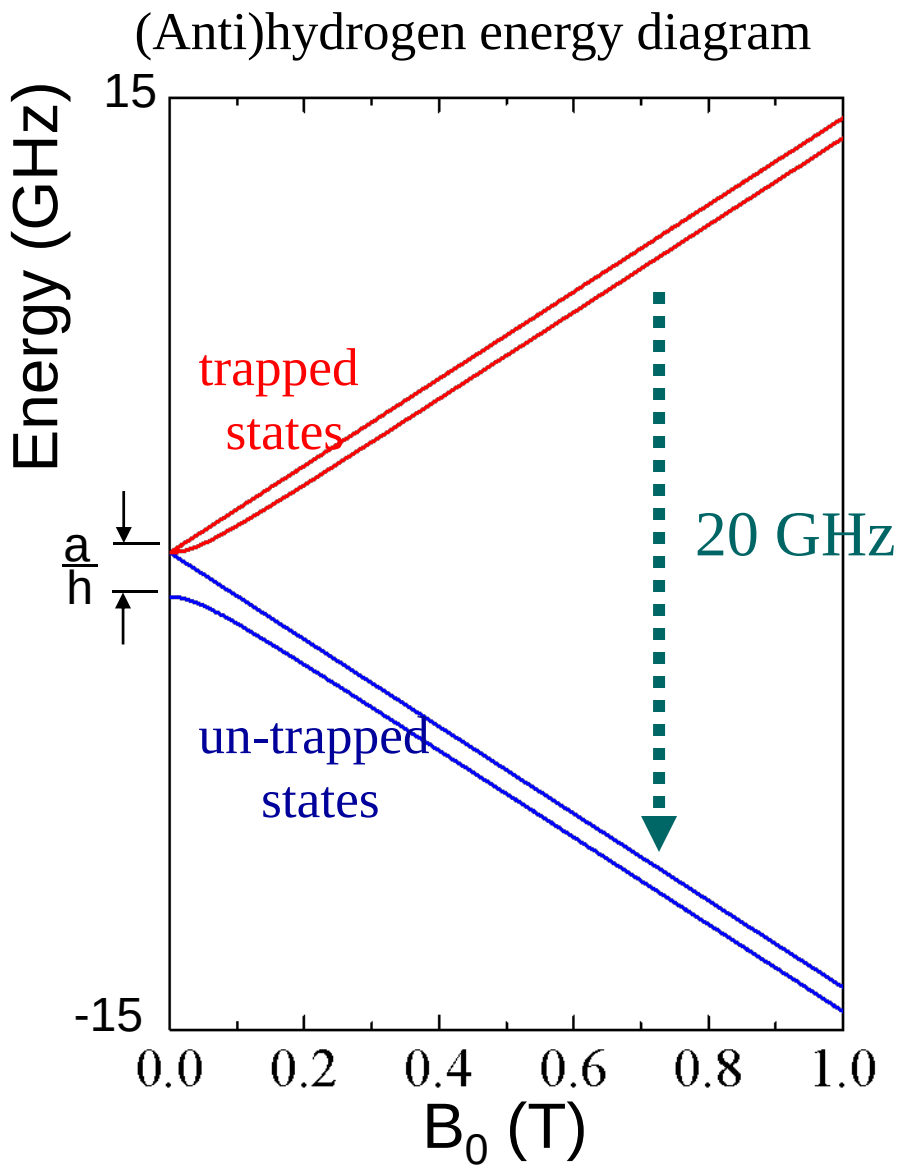
- **Doppler effect cancels**
- **High precision in matter sector**
- **test of CPT theorem**

"Hänsch Plot"



f(1S-2S) = 2 466 061 102 474 851(34) Hz - Hänsch group

Microwave Spectroscopy 1

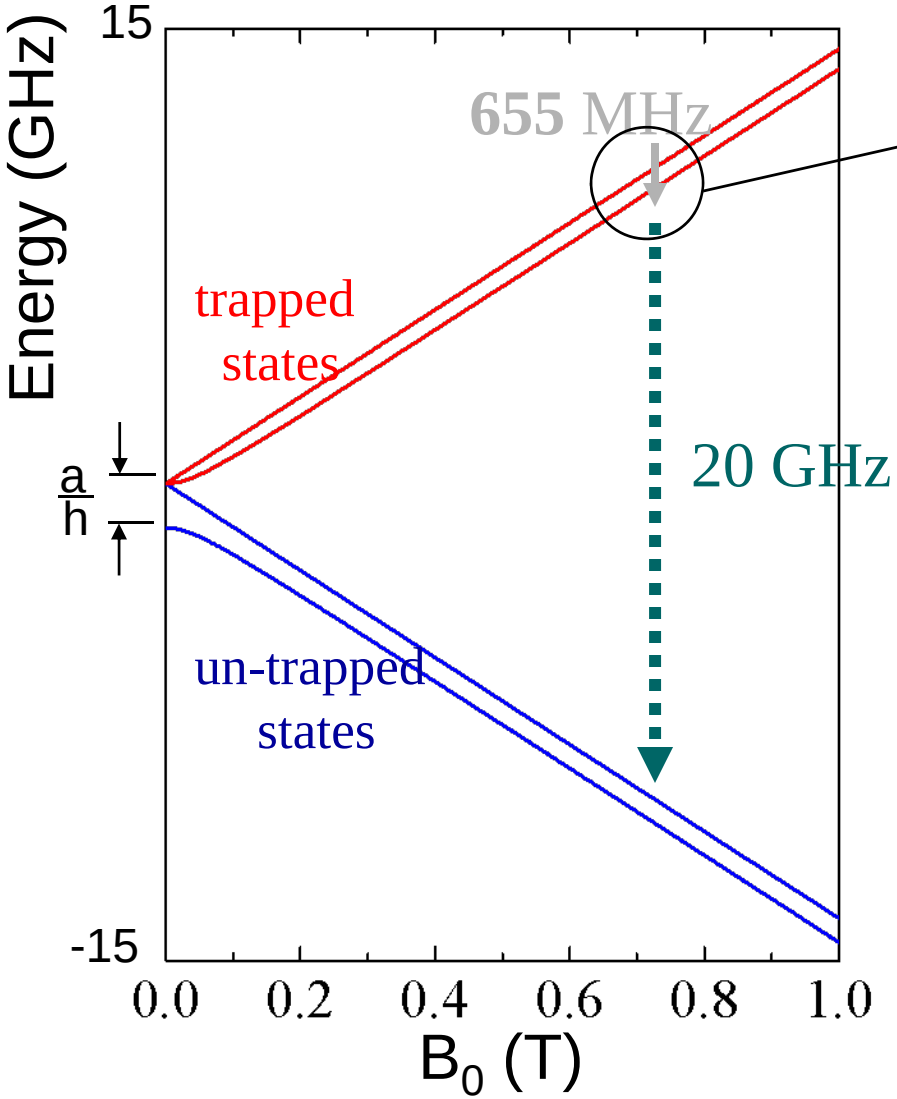


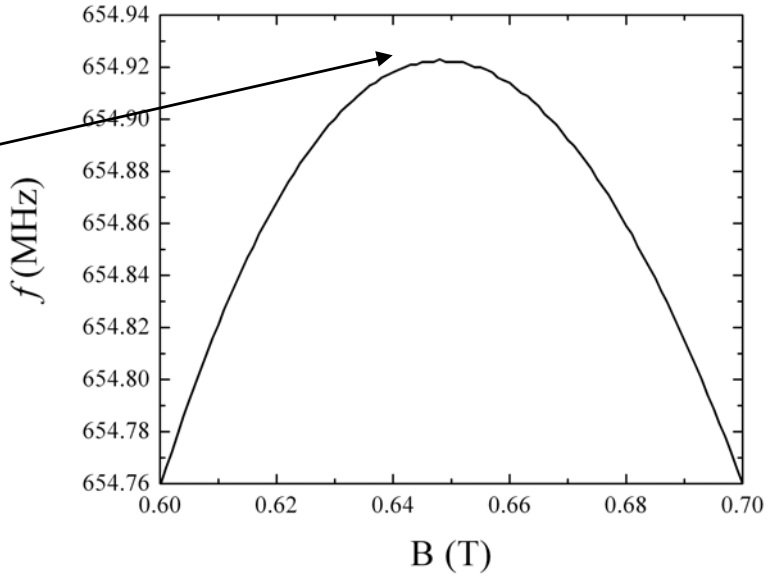
Positron Spin Resonance

- Pulsed μW at ~20 GHz
  trapped → un-trapped
- Look for annihilations
- Can start with a few atoms
- Can perhaps be done in existing apparatus; first resonant interaction with Hbar internal degrees of freedom

Microwave Spectroscopy 2

(Anti)hydrogen energy diagram



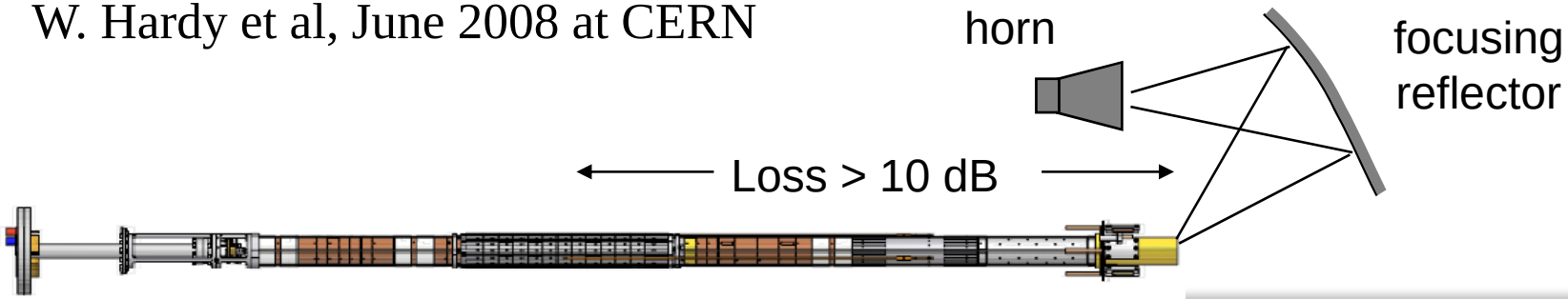


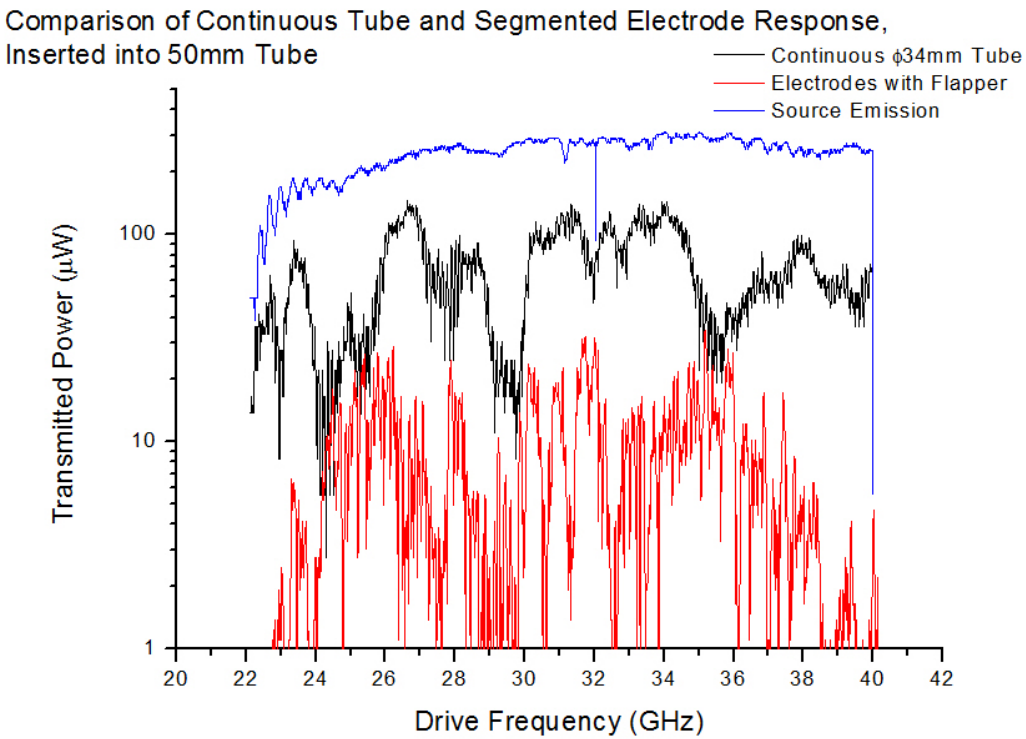
NMR (pbar spin flip)

- 655 MHz at magic 0.65T turning point: insensitive to 1st order B inhomogeneity
- Double resonance w/ PSR

Microwave Tests at CERN & SFU

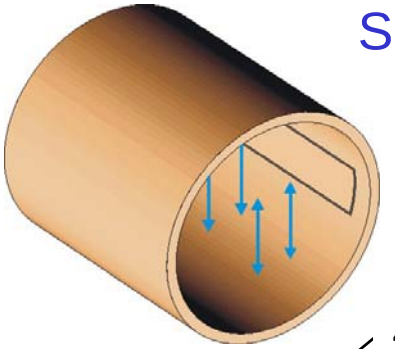
W. Hardy et al, June 2008 at CERN





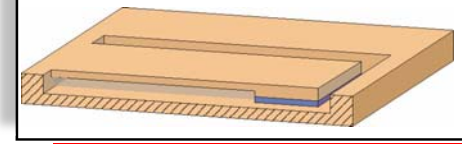
Plasma compatible resonator

M. Hayden et al. 2008



SFU prototype
f_0: 600-800 MHz
Q: 100-300

4 cm



opposed finger-like structures

Laser Spectroscopy

To accurately measure the energy level structure of anti-hydrogen for comparison with the energy level structure of hydrogen as a test of CPT.

General Experimental Procedure:

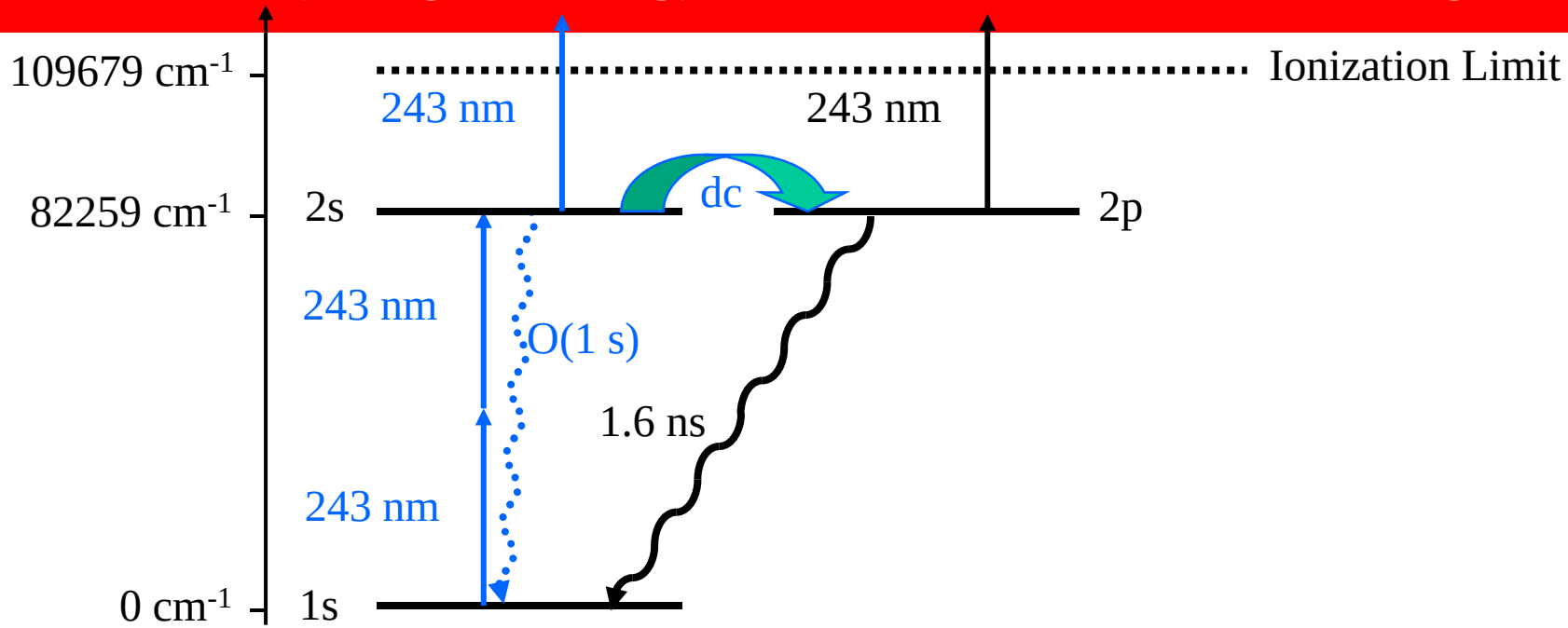
Stably trap anti-hydrogen in a magnetic trap for seconds

Optically drive a resonant transition in anti-hydrogen from n = 1 to n = 2.

Selectively remove n = 2 state anti-hydrogen from the magnetic trap

Efficiently detect the anti-matter expelled from the magnetic trap

(Anti-)hydrogen Energy Levels (n = 1, 2) and couplings



Other 2p Couplings: **Photo-ionization** **Spontaneous Decay**

single-photon ionization for $\lambda < 335$ nm

Single-photon allowed

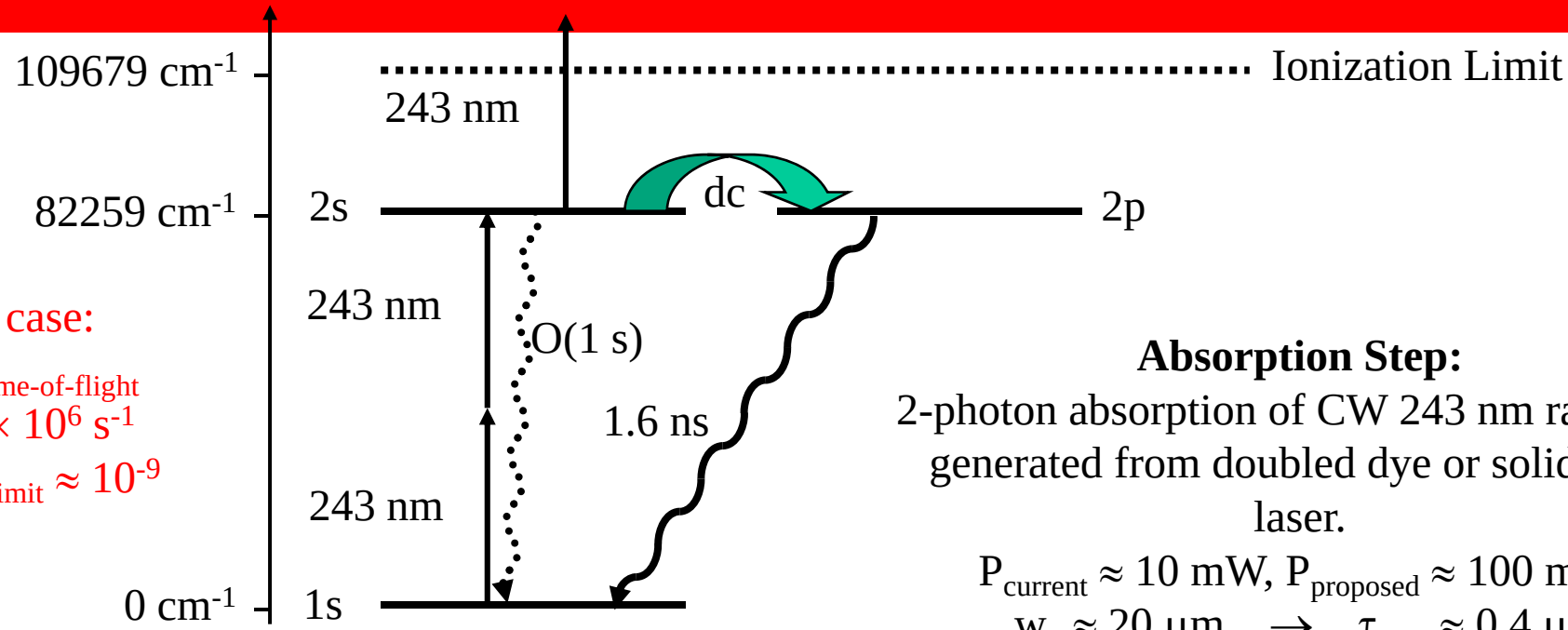
e.g. $\lambda = 243$ nm

$\Gamma_{2p,\ ion..} \cong 6.6\ I$ [(b)]

$\Gamma_{2p\ Spont..} \cong 6.3 \times 10^{8}\ s^{-1}$

[(b)] A. Burgess, MNRAS **69**, p.1 (1965)

CW Antihydrogen 1s – 2s Laser Spectroscopy *



In this case:

$\Gamma_{sys} = \Gamma_{time\text{-}of\text{-}flight}$

$\Gamma_{sys} \approx 2 \times 10^{6}\ s^{-1}$

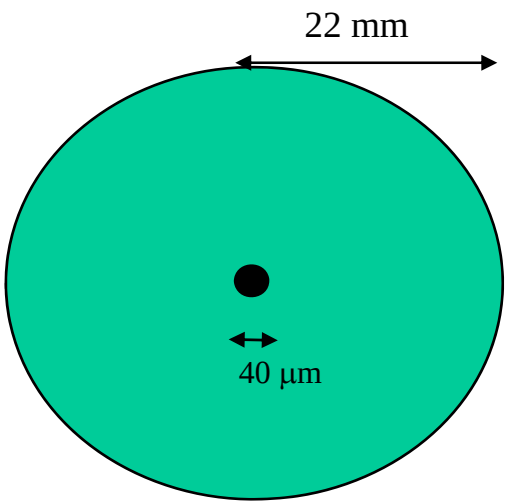
$Accuracy_{limit} \approx 10^{-9}$

Absorption Step:

2-photon absorption of CW 243 nm radiation generated from doubled dye or solid state laser.

$P_{current} \approx 10$ mW, $P_{proposed} \approx 100$ mW

$w_o \approx 20\ \mu m \quad \rightarrow \quad \tau_{pass} \approx 0.4\ \mu s$



Pb_{pass} = excitation prob. / pass through laser beam

$Pb_{pass} = \Gamma_{1s \leftrightarrow 2s} \times \tau_{pass}$

Time to unit excitation = $Pb_{pass}^{-1} \times T_{pass}$

Time to unit $excitation_{10mW} \approx (2 \times 10^{-6})^{-1}$ x 0.4 s

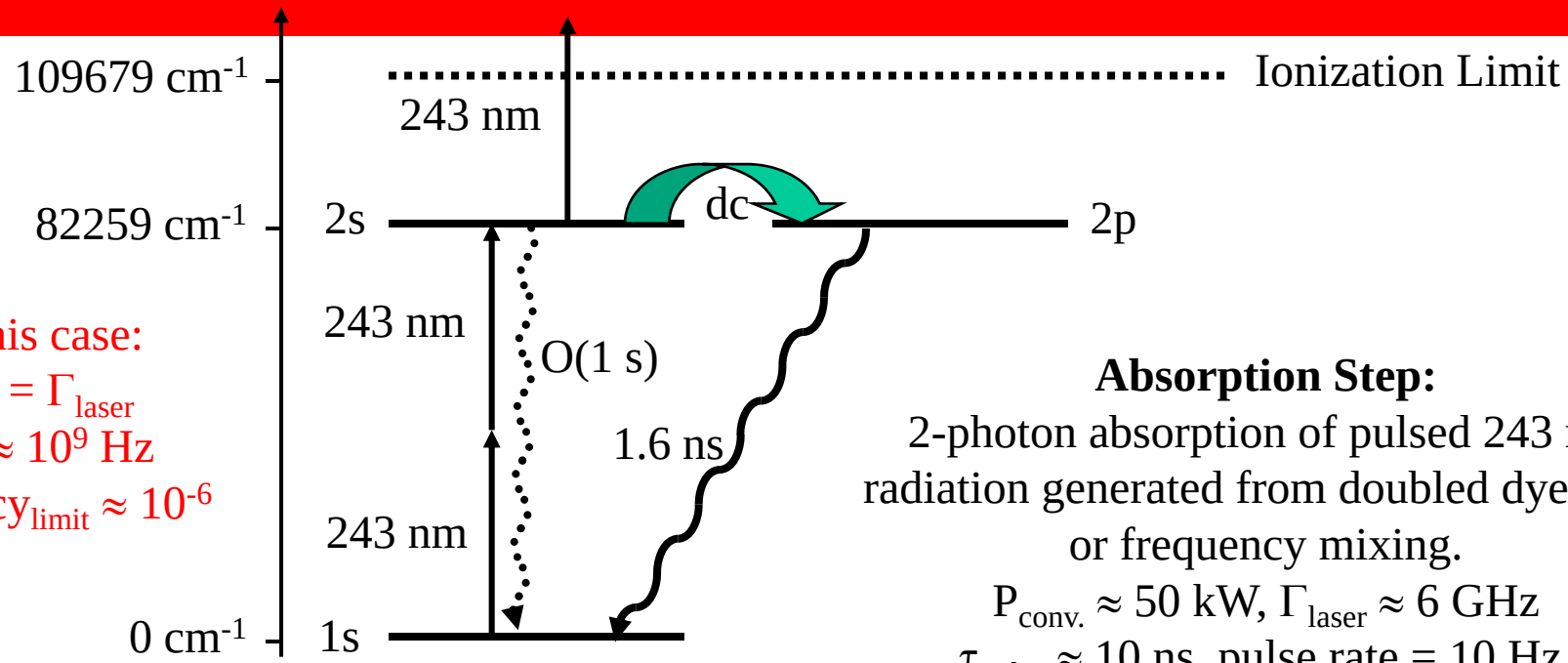
Time to unit $excitation_{10mW} \approx 2$ x 10^{5} s > **50 hours**

Signal $Rate_{10mW}$(100 Hbar) ≈ 1 count per 1800 s

Signal $Rate_{100mW}$(100 Hbar) ≈ 1 count per 18 s

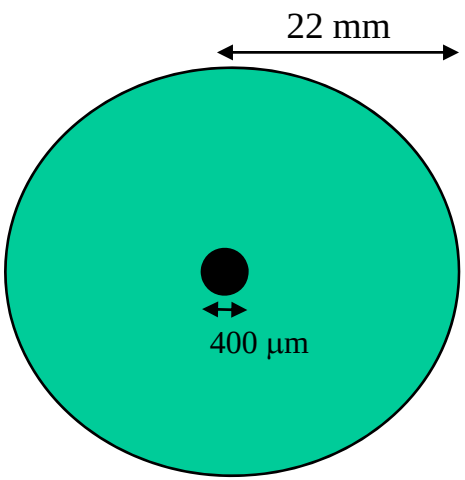
* From C. Cesar; Can. J. Phys. manuscript

Pulsed Antihydrogen 1s – 2s Laser Spectroscopy



In this case:
$\Gamma_{sys} = \Gamma_{laser}$
$\Gamma_{sys} \approx 10^9$ Hz
$\text{Accuracy}_{limit} \approx 10^{-6}$

Absorption Step:
2-photon absorption of pulsed 243 nm radiation generated from doubled dye laser or frequency mixing.
$P_{conv.} \approx 50$ kW, $\Gamma_{laser} \approx 6$ GHz
$\tau_{pulse} \approx 10$ ns, pulse rate = 10 Hz.



Set laser width to saturate transition in each pulse:

$$\Gamma_{1s \leftrightarrow 2s} \times \tau_{pulse} = 7\times10^{-7}\, I^2\, \tau_{pulse} / \Gamma_{sys} = 1$$

$$\Rightarrow \quad r_{laser} \approx 233\ \mu m$$

Excitation rate = excitation/pulse × pulse rate × pulse fraction

$$\text{Excitation rate}_{conv} = 1 \times 10\ s^{-1} \times (0.233mm / 22mm)^2 = 10^{-3}\ s^{-1}$$

$$\text{Time to unit excitation}_{conv.} \approx 900\ s = 15 \text{ minutes}$$

$\text{Signal Rate}_{conv.}$(100 Hbar) ≈ 1 count per 9 seconds
Signal Rate_{SLM}(100 Hbar) ≈ 1 count per 3 seconds
Signal Rate_{NLM}(100 Hbar) ≈ 3.5 - 7 counts per second

ALPHA Current Outlook

Concentrate on demonstration of trapping of Hbar – 2009/2010

Modify existing apparatus for first (microwave) atomic physics – 2010/2011

Design and build new apparatus optimized for laser spectroscopy – 2009-2011

Spectroscopy on trapped antihydrogen – 2011 - ???

A Few Words About Elena

- We are making the transition from "learning curve" limited physics to statistics limited physics

- The trapping experiment we performed in 2008 is marginally viable at the AD

- With a factor of 10 - 100 more pbars, we could much more rapidly explore the trapping parameter space – hopefully we will achieve trapping without this

- This extra factor will be even more important when atomic physics studies begin in earnest

- ELENA seems to be essential for optimizing the output of rare-event physics at the AD

- Collaboration from outside (S. Chattopadhyay) very encouraging

- FLAIR is not a substitute for the AD; effort should be focused at CERN; diluting the resources seems ill-advised for our specialized community

Final Thoughts

The AD is a unique facility in the world and will be without equal in the foreseeable future.

The physics program of the AD is thriving and expanding; research with antimatter spectroscopy and gravitation have a long time horizon.

We should agree as a community to do everything possible to keep the AD running as long as important physics challenges remain.

In case you are confused by Hollywood: The trapped antimatter at CERN is in the AD hall, not at the LHC.