α Project ALPHA

Antihydrogen Laser PHysics Apparatus

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Riken:

Federal

Thanks to CERN AD Staff!

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α ALPHA "ROADMAP"

First Production

Steps Along on the Way

2003 ⇒ ?

Quantum State Manipulations

Laser induced formation

- First laser-antiatom interactions
- e+ temperature measurement
- 3-body plasma effects

attempt 2006
sufficient quantities 3-5 years?

Stable Trapping

Non-neutral plasma stability studies

- Resonant particle transport
- Trapped particle modes
- Quadrupole vs. multipole effect

Precision Spectroscopy

1s-2s spectroscopy

- anything imaginable

~ 2009

?

Planck Scale Physics
CPT Violation
Gravity

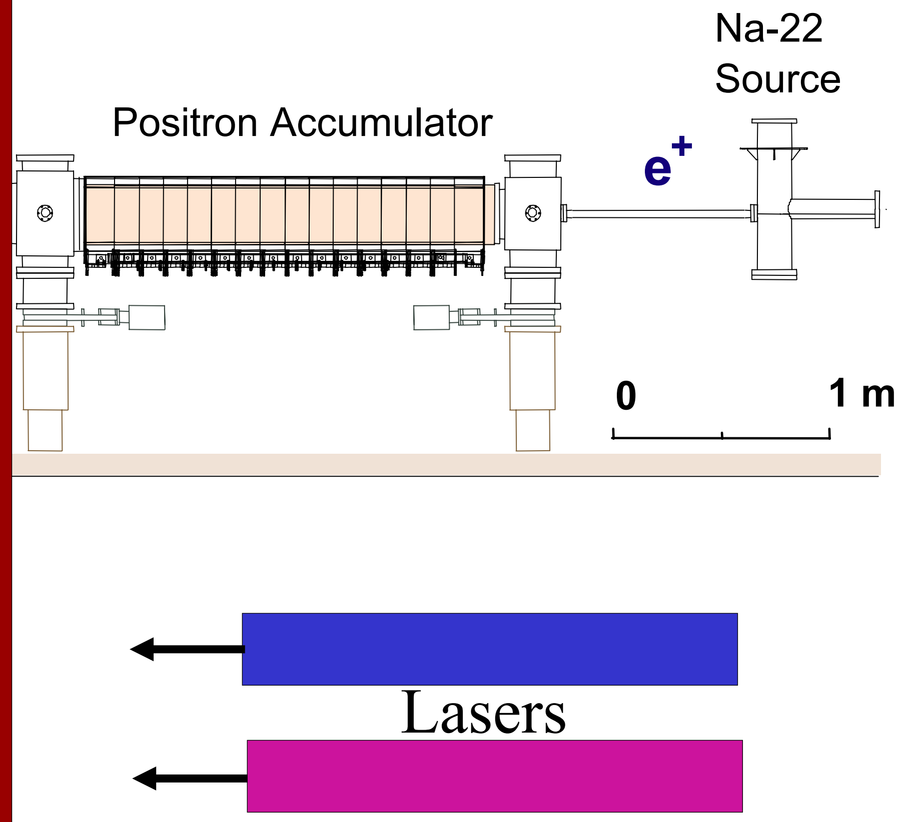
Strengths and Expertise

- World's strongest cold e+ source
- Precision and high-power lasers
- Non-neutral plasmas
- Comprehensive detector capability
- Hydrogen trapping and spectroscopy

Aarhus, Berkeley, Liverpool, Rio, RIKEN, Swansea, Tokyo, TRIUMF

α This worked. What Happens Next?

Insert here:
A new purpose-built system for antihydrogen trapping and spectroscopy



α Philosophy & Strategy

• The original vision of the AD program - conducting tests of CPT symmetry based on antihydrogen spectroscopy - remains our unique focus

• We believe that it is essential to trap antihydrogen atoms in order to
g
C

We need access to antiprotons again as soon as possible (hopefully more of them, Pavel)

Antihydrogen formation cannot be simulated offline

•
b

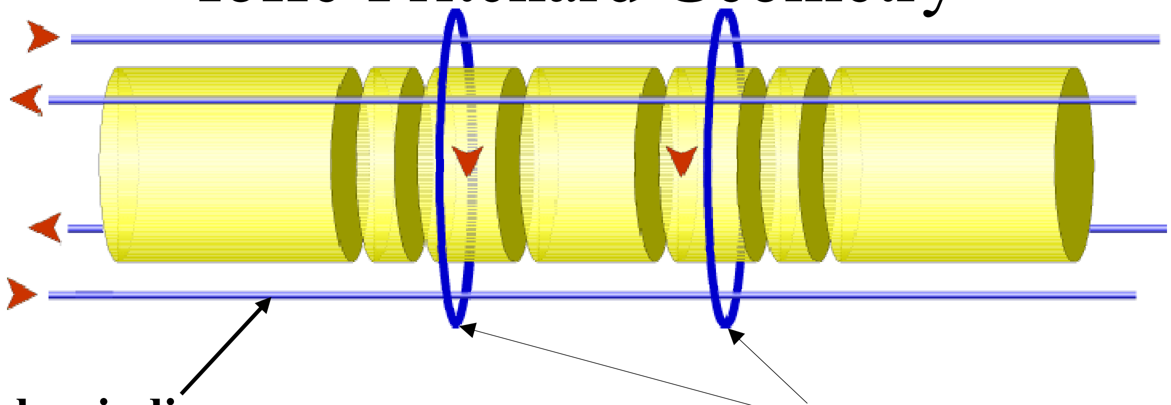
•
antihydrogen: mixed plasmas of cryogenic constituents - with possible laser
enhancement

• Trapping is the main goal: investments and design considerations for the new apparatus will prioritize the trapping hardware

• Offline trapping studies based on variable-field, superconducting, multipole magnets are essential for making design decisions for the new apparatus. These are underway.

α Trapping Neutral Anti-atoms

Ioffe-Pritchard Geometry



Aside: high n-states could have higher μ

$$\vec{B}_Q = gr\sin(2\theta)\hat{r} + gr\cos(2\theta)\hat{\theta} = gy\hat{x} + gx\hat{y}$$

Solenoid field is the minimum in B

Can we superpose this on a nested trap?

α Quadrupole Questions

- **What is the necessary field strength?** $$\Delta B = \sqrt{(B_z^2 + B_Q^2(r_t))} - B_z$$

  e.g. B_z= 3T; trap radius 1 cm; desired well depth 1T

  Quad gradient = 265 T/m ! (LHC 213 T/m @ 1.9 K)

  $\Rightarrow$ favors small solenoid fields; pbar capture and cyclotron cooling favor high solenoid field; may need a *rampable* superconducting solenoid

  $\Rightarrow$ need quad coils as close as possible to trap wall

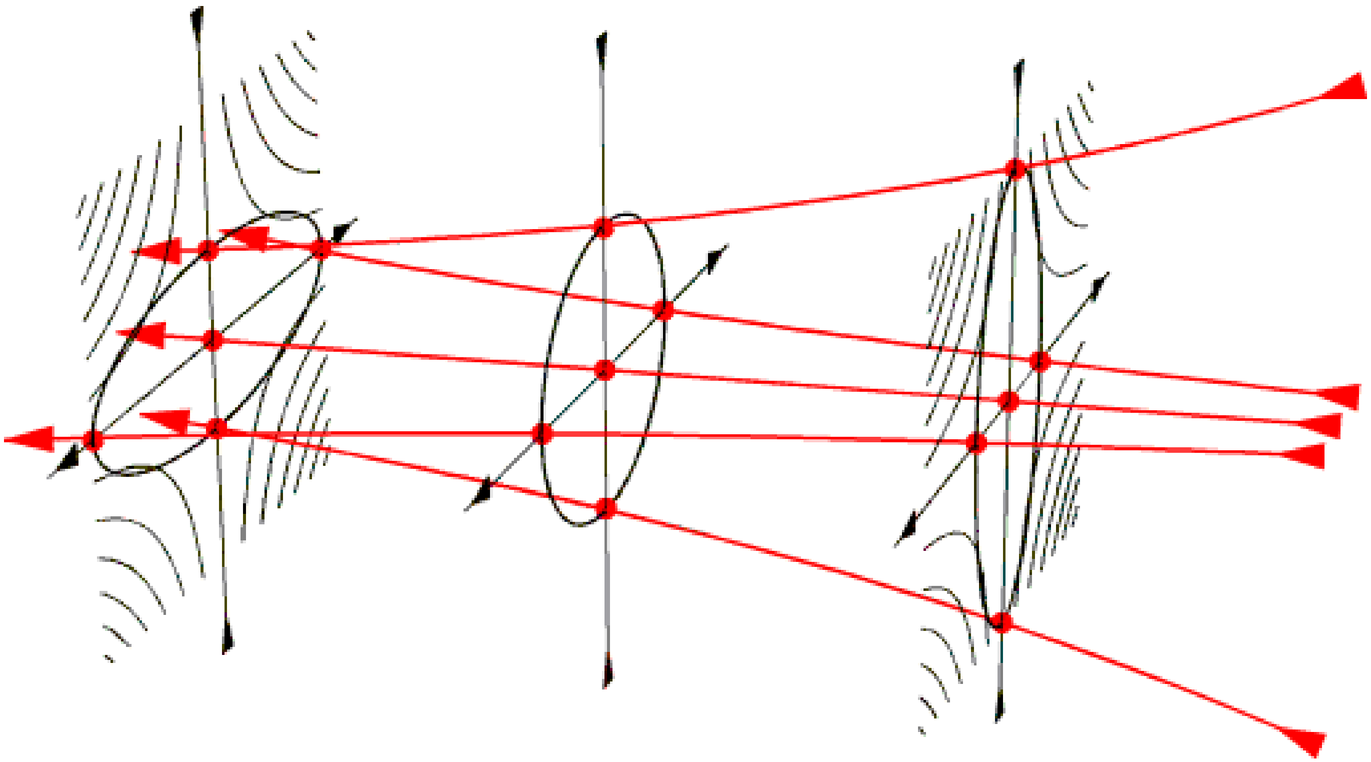
- **Do particles follow the field lines?**
- **Will the plasmas just disappear at the necessary field strengths?**

  E.P. Gilson and J. Fajans, PRL 90, 015001 (2003)

  T. Squires *et al., PRL* 86, 5266 (2001)

- **If they don't initially disappear, can they be mixed without disappearing?**
- **If they are mixed, is the density of overlap high enough to make H-bar?**

Field Lines with Quadrupole



Rotational symmetry broken: is there a *plasma* equilibrium?

Note: if antihydrogen production is 3-body; positron collisions are important: single particle stability not the relevant criterion

UC Berkeley: experimental (J. Fajans) and theoretical (J. Wurtele) studies

α Experiments at Berkeley

Superconducting solenoid B_{max}= 8T

Superconducting quadrupole g_{max}= 40 T/m

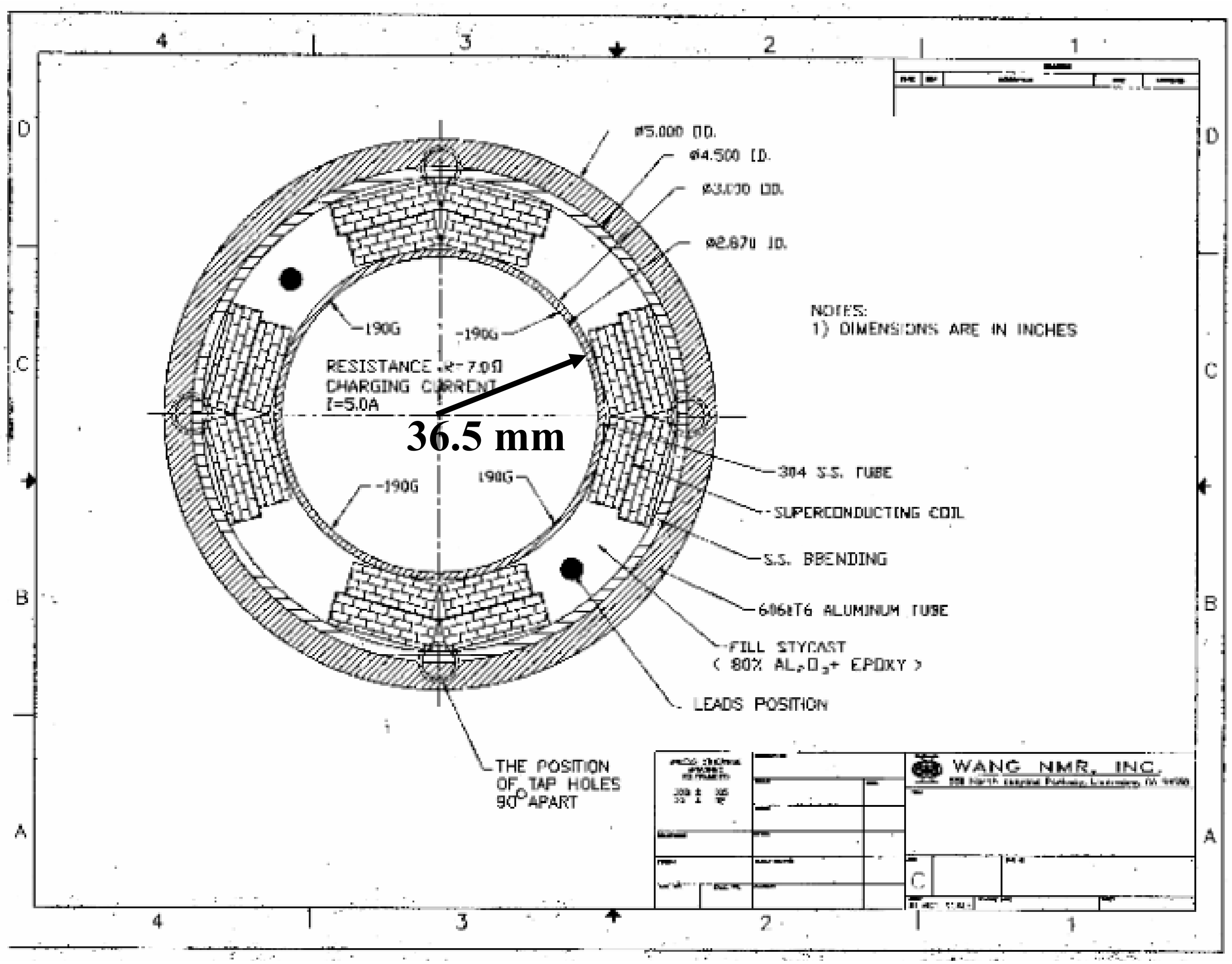
Electron plasmas N ~ 10^8; cryogenic temperature

Study lifetimes for different B, g; effect of ramping quad field; harmonic and square wells

Resonant effects believed to be important: must *vary* field

⇒ Scaling laws for lifetime: F(B,g)

α Berkeley Superconducting Quadrupole



Gradient 40 T/m; length 36 cm

Berkeley Experiment

Thanks to Michael Holzsheiter/Martin Shauer/LANL

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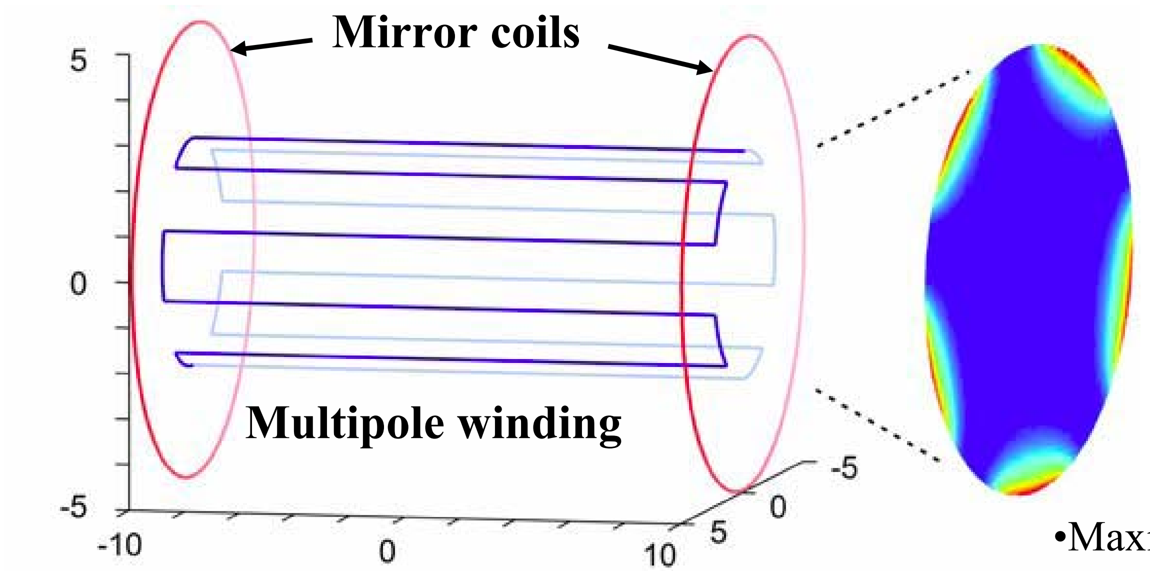
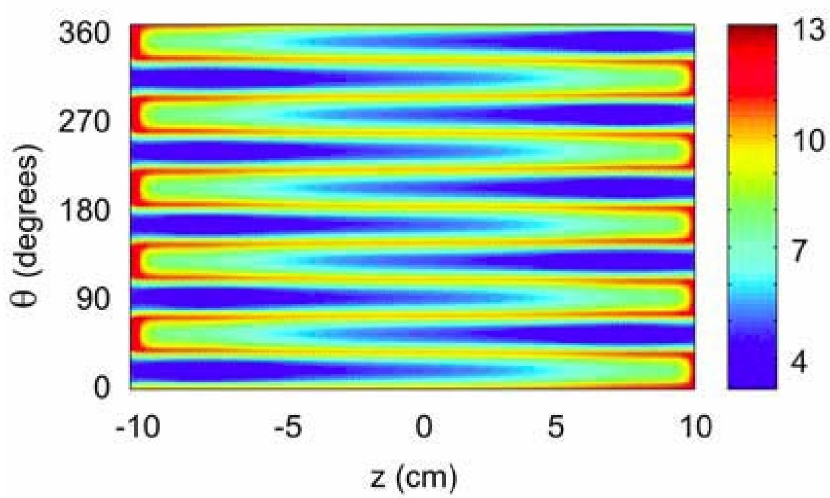
Berkeley Experiment

Plan B: Multipole Confinement



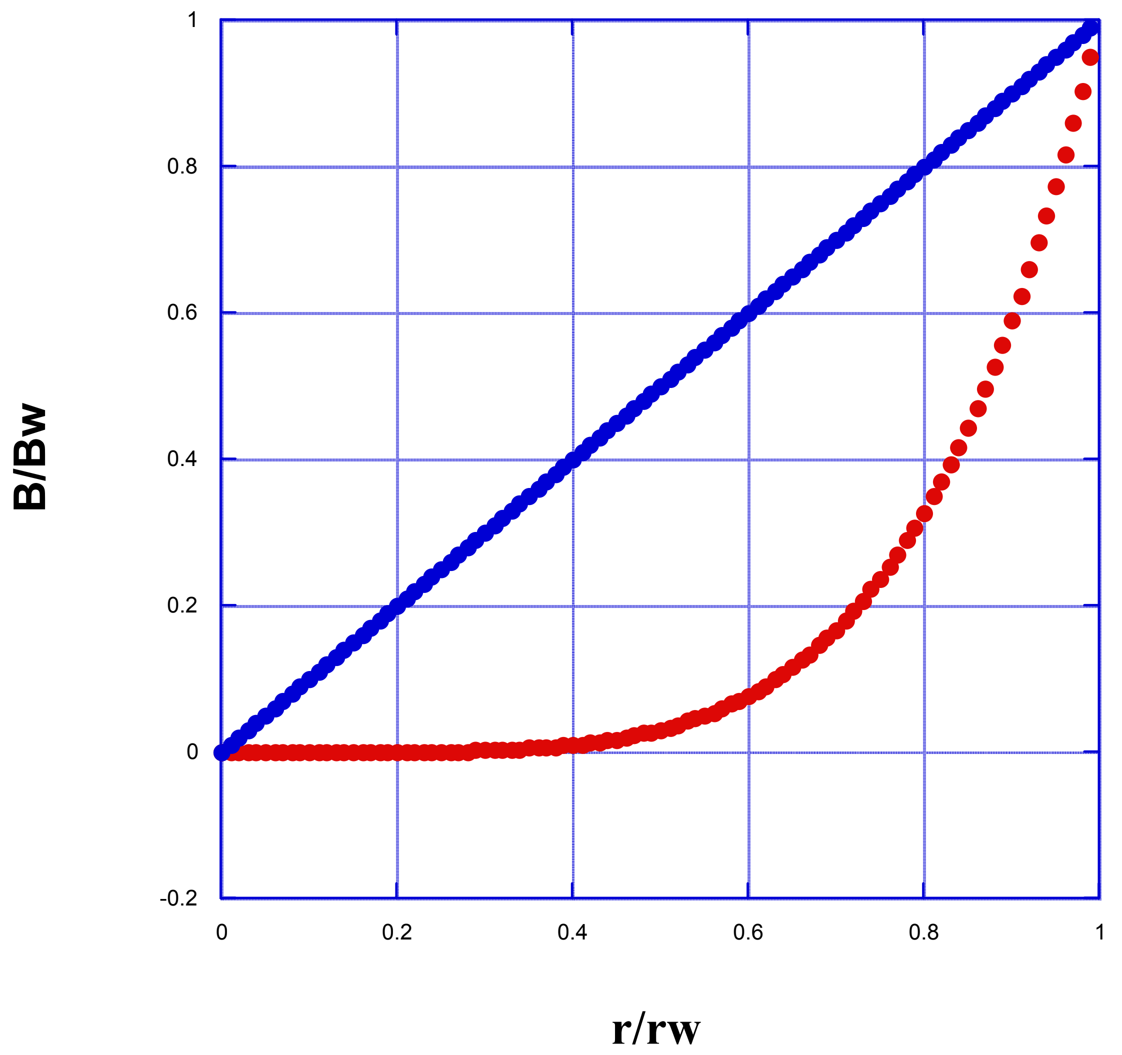


$$B_s = B_w \left(\frac{r}{r_w} \right)^{s-1}$$

- Maximum field (well depth) determined by current at wall: independent of order
- Less perturbation of plasmas near r=0
- Tradeoff between tight radial confinement and plasma perturbation determines optimum multipole order
- May need multipole + *rampable* quadrupole for laser physics

A. Schmidt and J. Fajans, NIMA 521, 318-325 (2004)

Quad vs. multipole (s=6)



Kurchatov-Berkeley Magnet

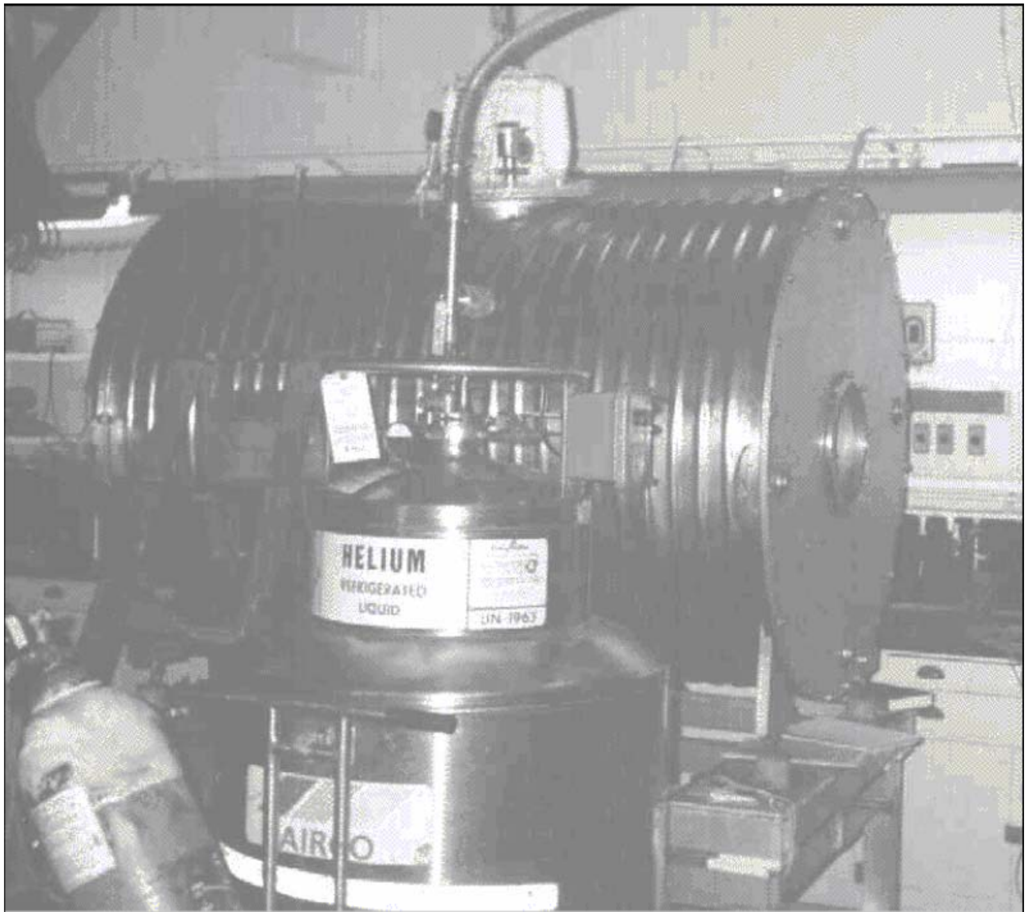
- 3 T, warm bore 26 cm diameter
- homogeneous region (10^{-3})
100mm diameter, 600 mm long

Concerns:

- Solenoid/multipole interaction forces can be huge

$$\vec{F} = \int \left(\vec{J} \times \vec{B}\right) dV$$

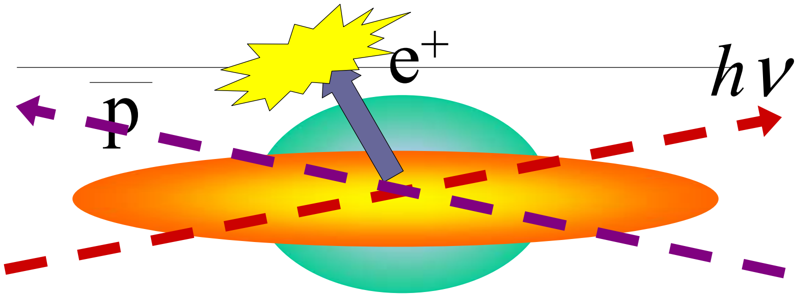
- May want to ramp this and multipole



CRYOSTAT.JPG

α Laser Stimulated Combination

Inspired by A. Wolf 1993



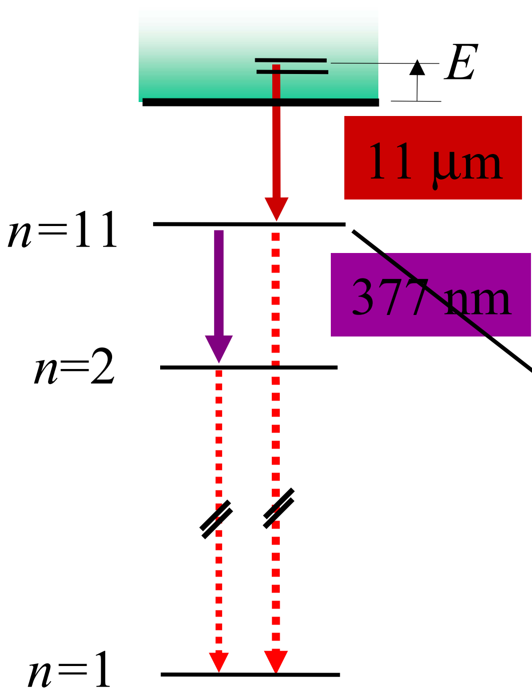
Measure production rate vs. frequency

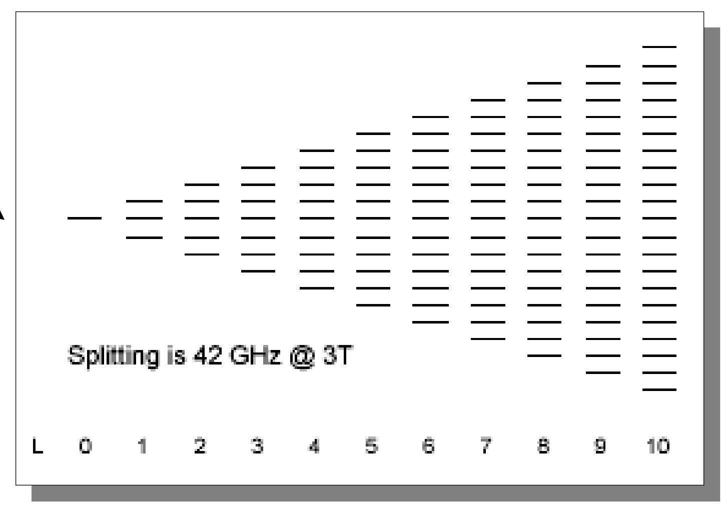
1^{st} step: tunable $^{13}C^{18}O_2$ laser (50W)

1^{st} resonant frequency depends on e^+ temperature

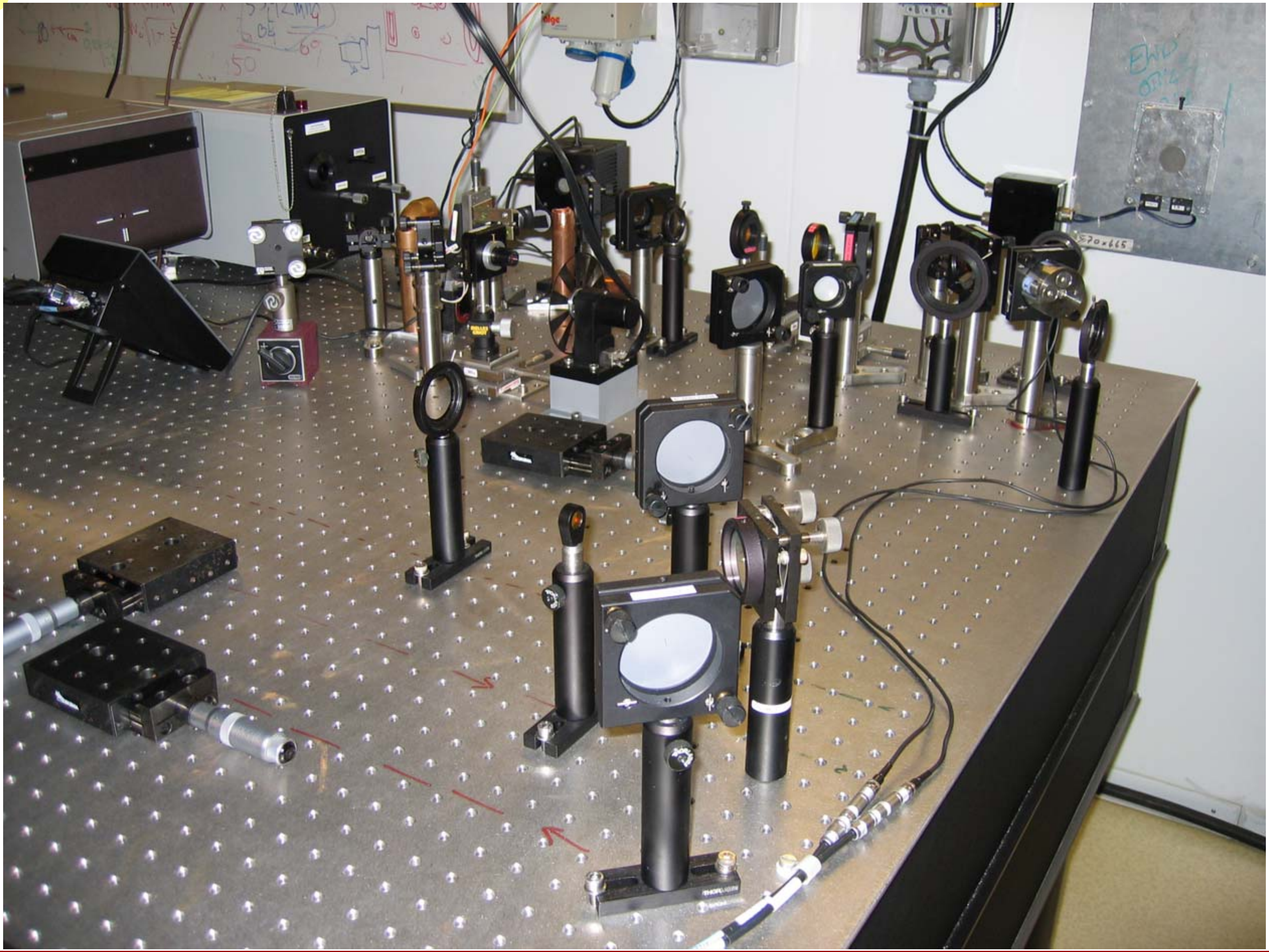
Realistic estimate: ~60 Hz

Tightly-bound quantum state

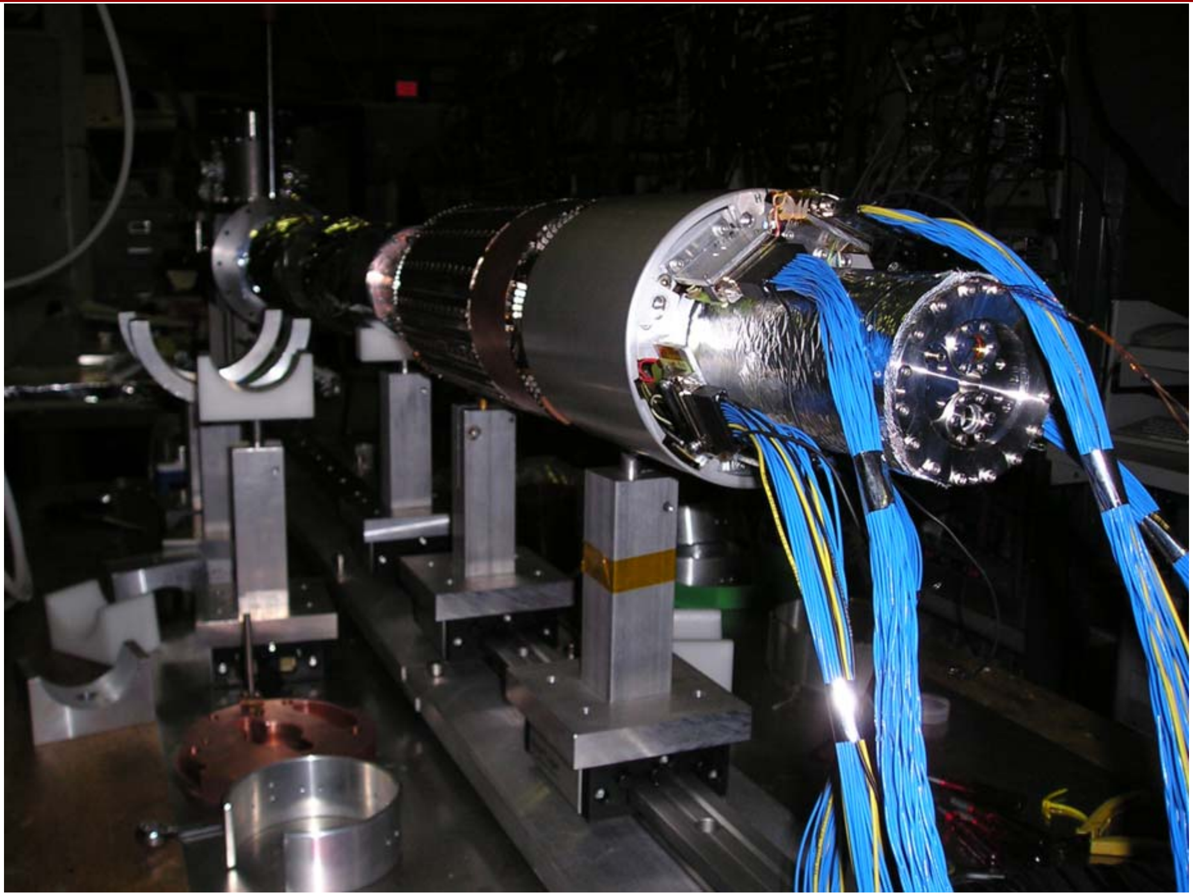




α Current Set-up in ATHENA Laser Lab



α Laser Stimulated Combination



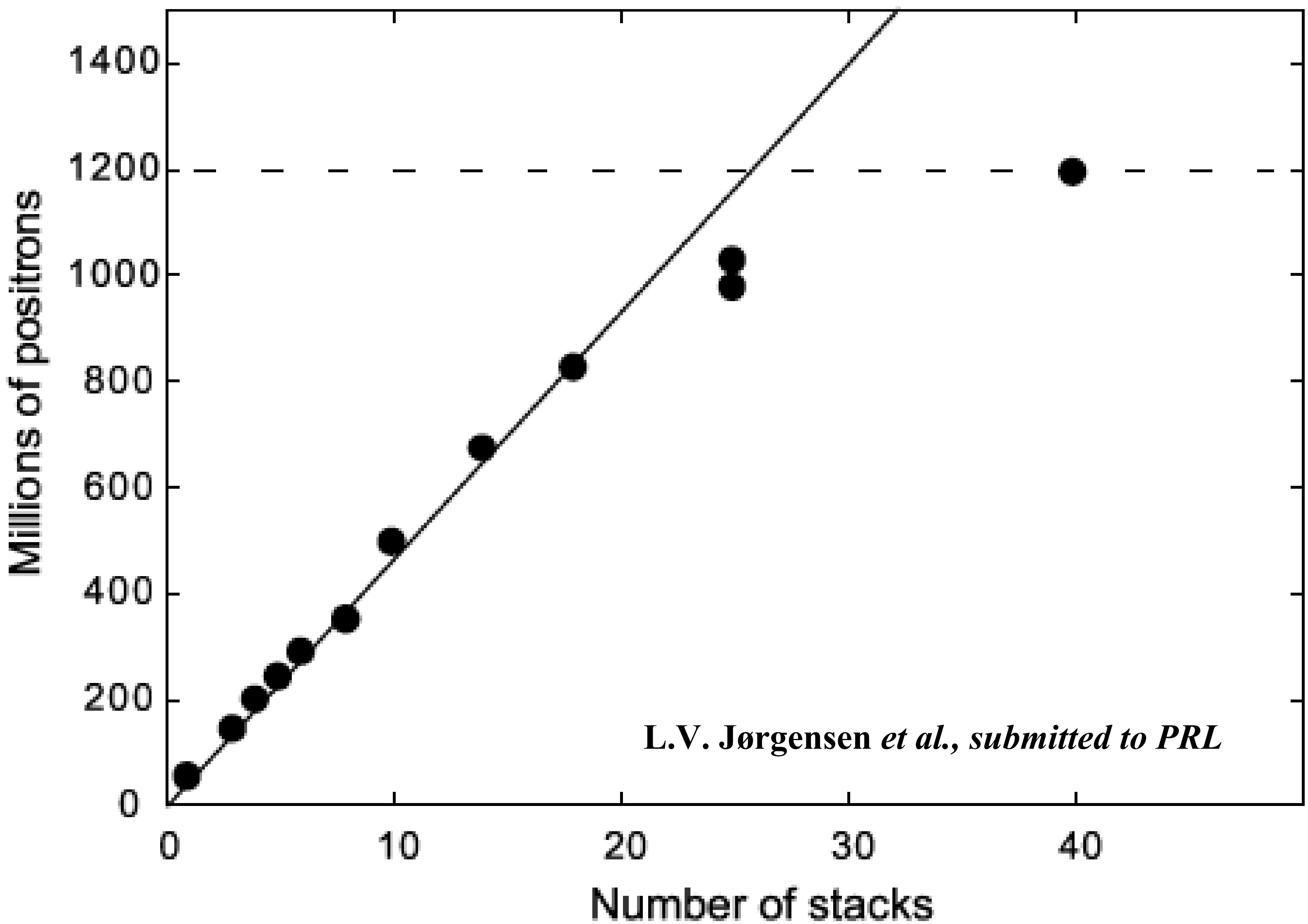
Trying now in ATHENA apparatus

Valuable experience with high-power laser in cryo system

Refine for ALPHA apparatus

Build-up cavity for more power; saturate larger spatial region

Positron Improvements



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Detection

•Need to confirm and optimize production w/o trapping fields

•Need to confirm and optimize production w/ trapping fields

•Need to verify trapping: probably by release of trapping fields

•For state-of-the-art multipoles, coil and support structure serious impediments to vertex detection (multiple scattering)

•ATHENA vertex reconstruction (~ 4mm resolution) based on straight-line fits to curved trajectories in solenoid field without momentum information; multipole fields are maximum at trap wall where vertices lie

•GEANT 4 Monte Carlo (Tokyo group) being used to study these issues

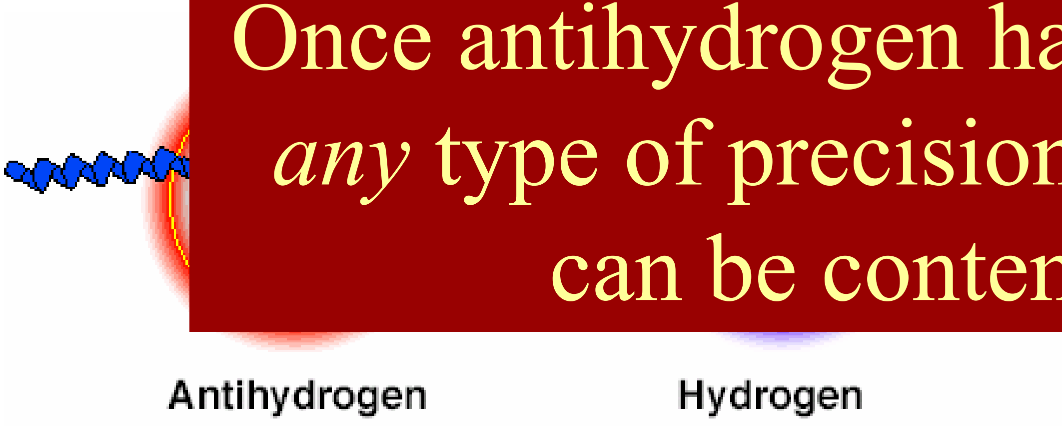
•Retain vertex detection if possible; avoid cryogenic detector if at all possible

•Liverpool will lead detector development for ALPHA

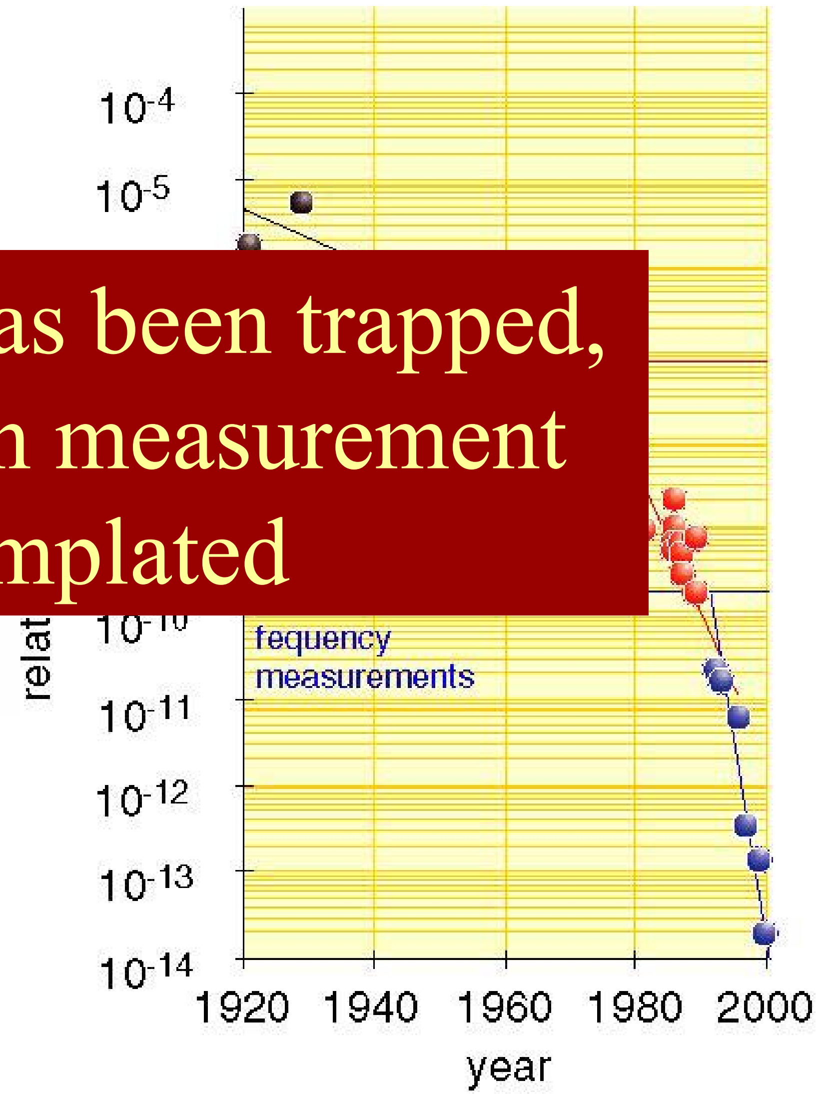
•ATRAP field ionization detection could be very useful initially

α Precision Spectroscopy - Still the Goal

1s-2s two-photon spectroscopy



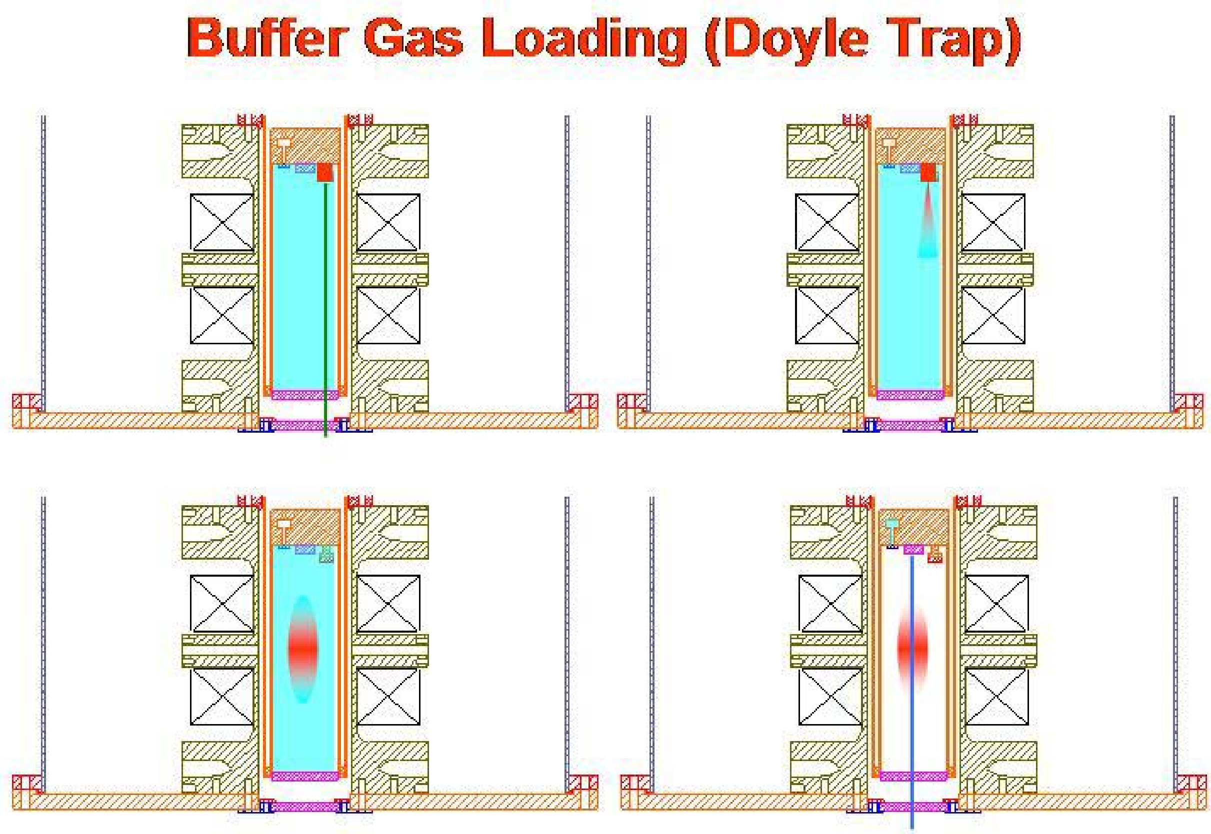
“Hänsch Plot”



Once antihydrogen has been trapped, *any* type of precision measurement can be contemplated

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

α Hydrogen Reference Cell (Rio)

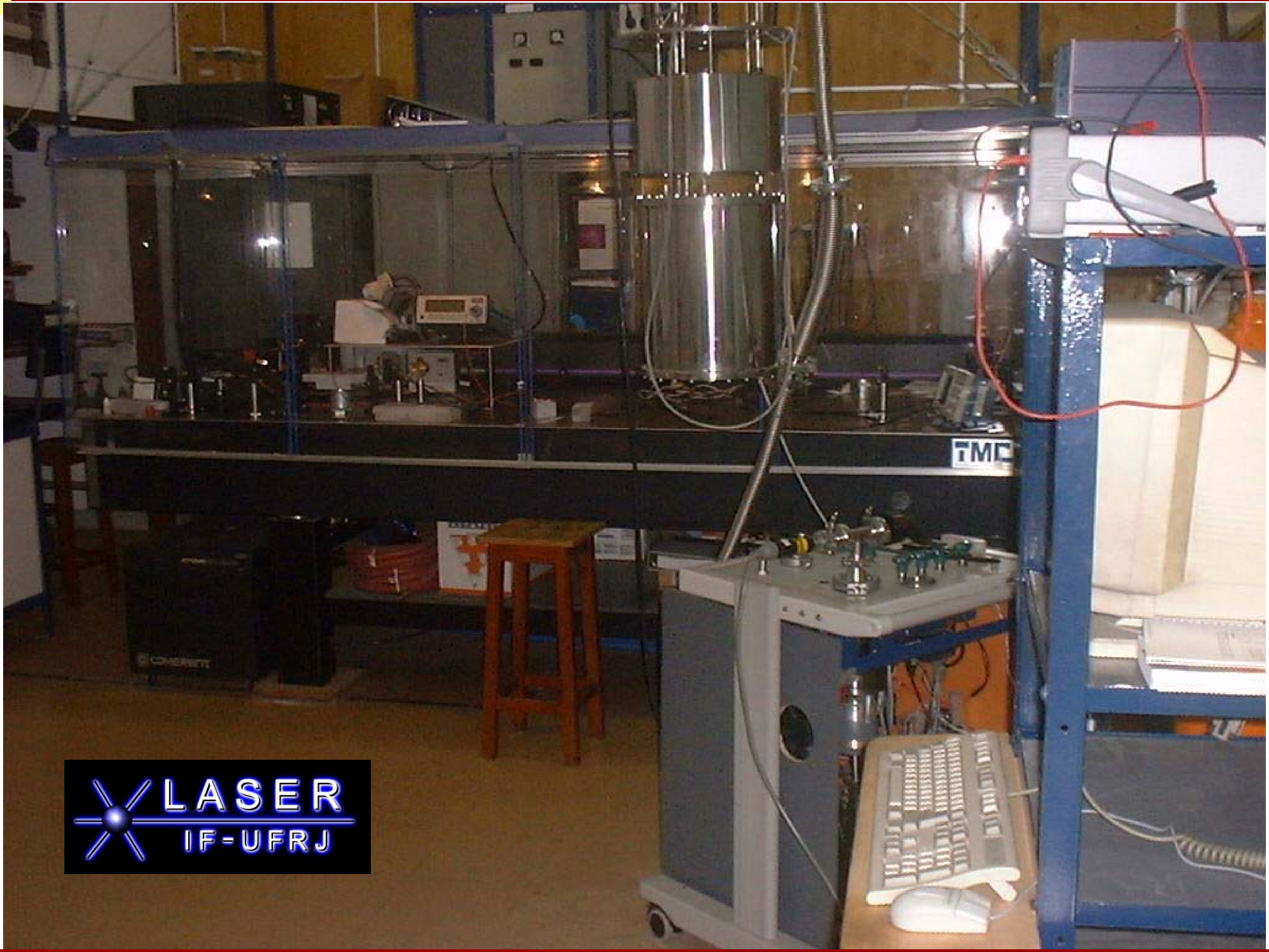


Trap hydrogen at 1.3 K by laser ablation; He buffer gas cooling

Evaporative cooling to sub-Kelvin temperatures for precision spectroscopy

Frequency reference for Hbar comparison

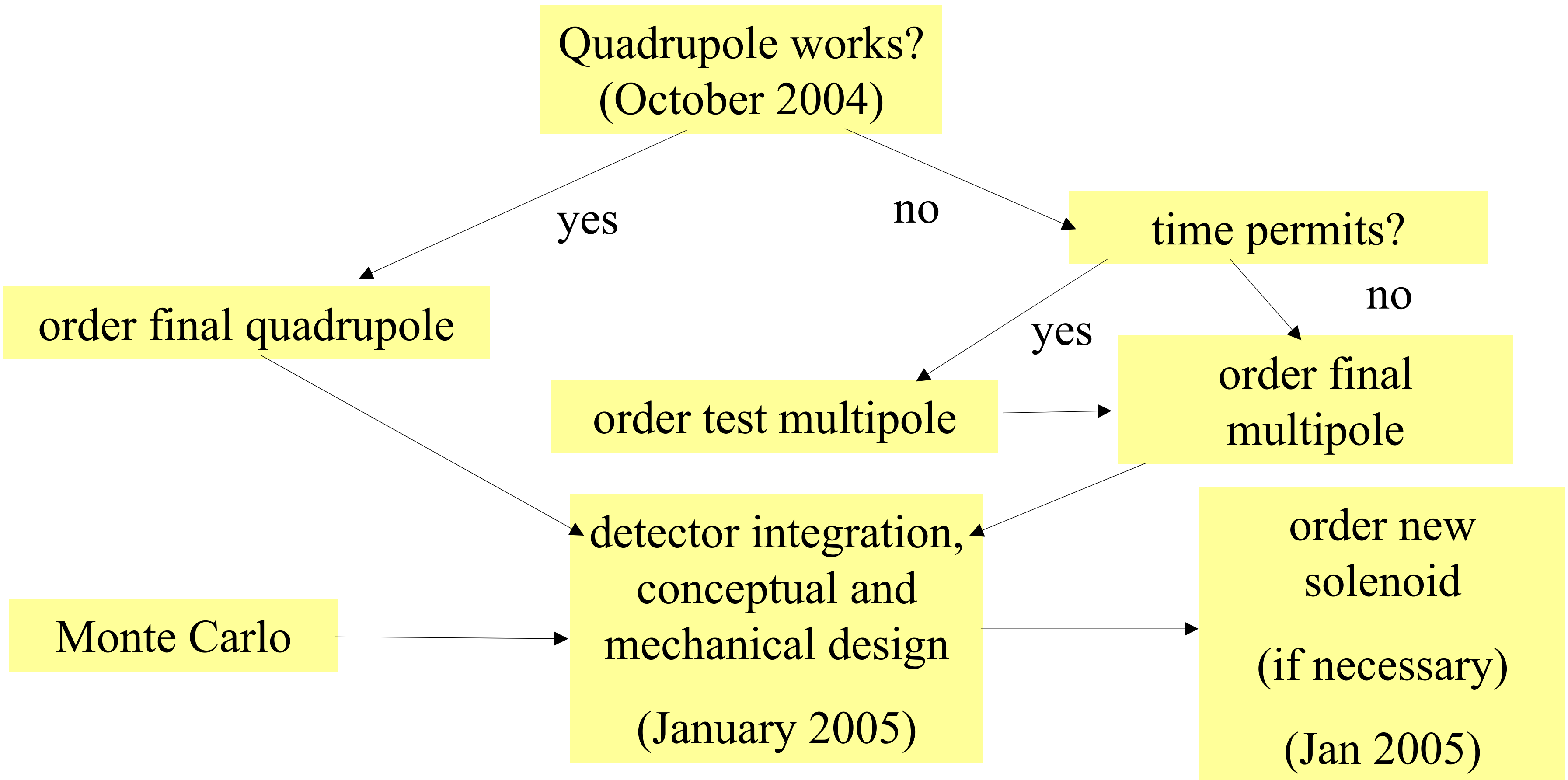
Rio Buffer Gas Trap



α Development at CERN

- Cryo tests: e.g. cryostat with warm magnet bore
- Vacuum & cryo tests: laser windows , etc.
- New trap construction techniques: need $r_m \sim r_t$
- Large positron plasmas for more tightly bound Hbar
- Laser development: 1s-2s stabilized to 1 kHz, CO_2 laser (power buildup, different isotopic mixtures)
- Hydrogen source for laser development

Development Flow Chart



α Summary

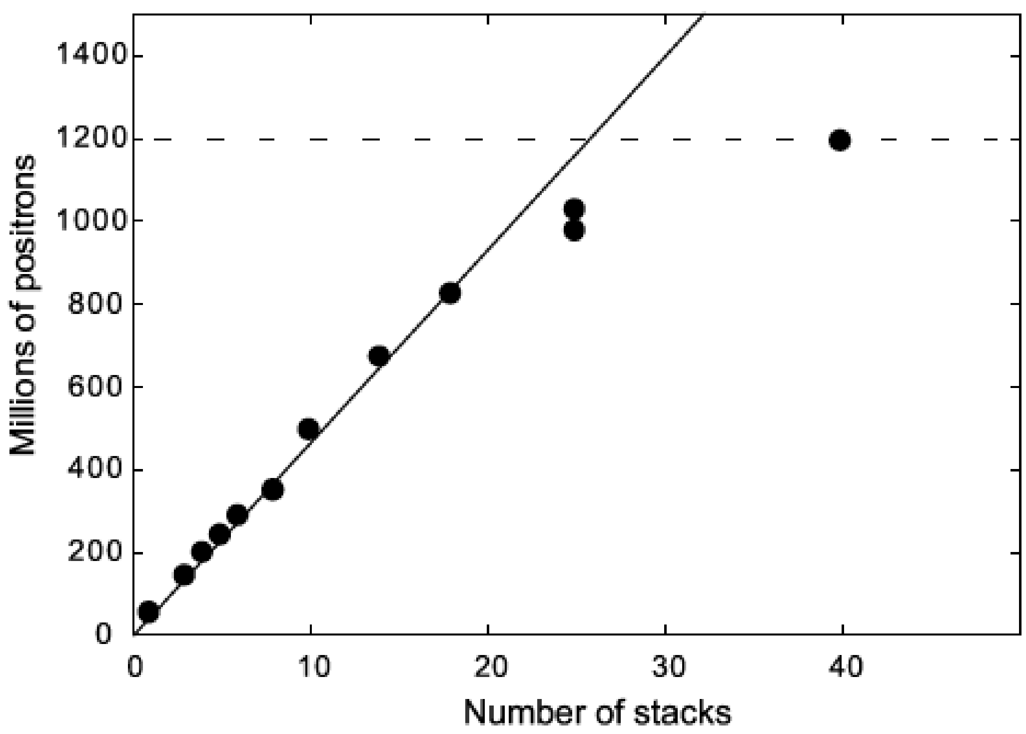
α**ALPHA is:**

α **a new collaboration having all of the necessary expertise and resources to realize the goals of antihydrogen trapping and spectroscopy**

α **dedicated to starting physics again when the AD program resumes in 2006**

α **anxious to get on with it**

α



1400
1200
1000
800
600
400
200
0
Millions of positrons
0
10
20
30
40
Number of stacks