THE ALPHA COLLABORATION

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University of British Columbia, Canada

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University of Calgary, Canada

Imperial College London

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University of Manchester, UK

NRCN - Nuclear Res. Center Negev, Israel

Purdue University, West Lafayette, USA

Federal University of Rio de Janeiro, Brazil

Stockholm University, Sweden

Simon Fraser University, Canada `

TRIUMF, Canada

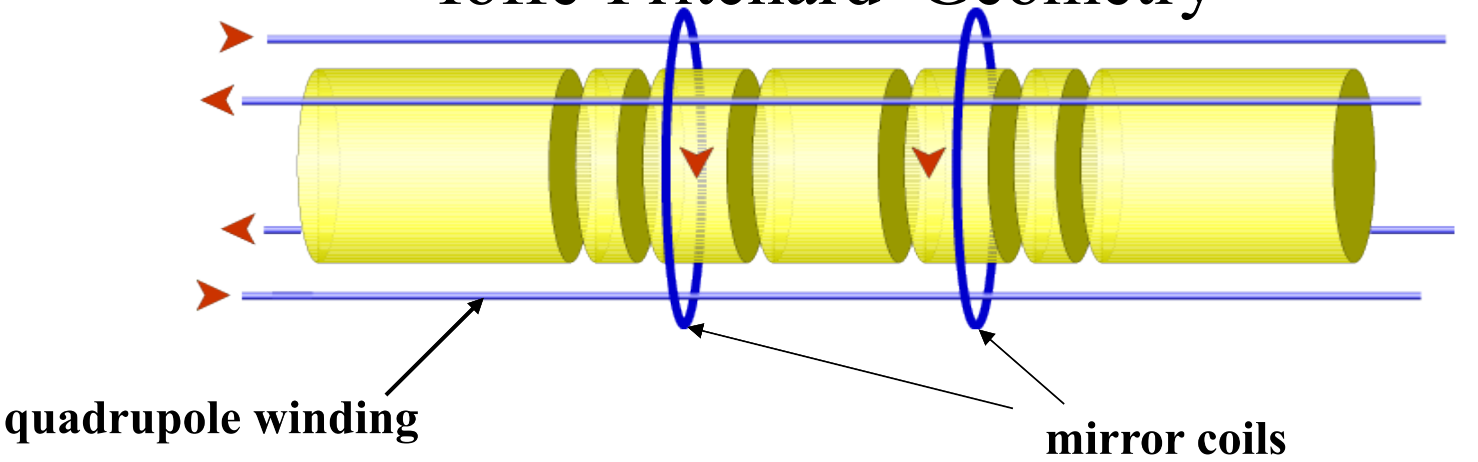
University of Wales Swansea, UK

Cockcroft Institute, UK

York University, Canada

Trapping Neutral Anti-atoms?

‘Ioffe-Pritchard’ Geometry



$$U = -\overline{\mu} \cdot \overline{\mathbf{B}}$$

Well depth ~ 0.7 K/T

ALPHA trap depth ~0.5 K

ALPHA Strategy: Demonstrating Trapped Antihydrogen (from 2005)

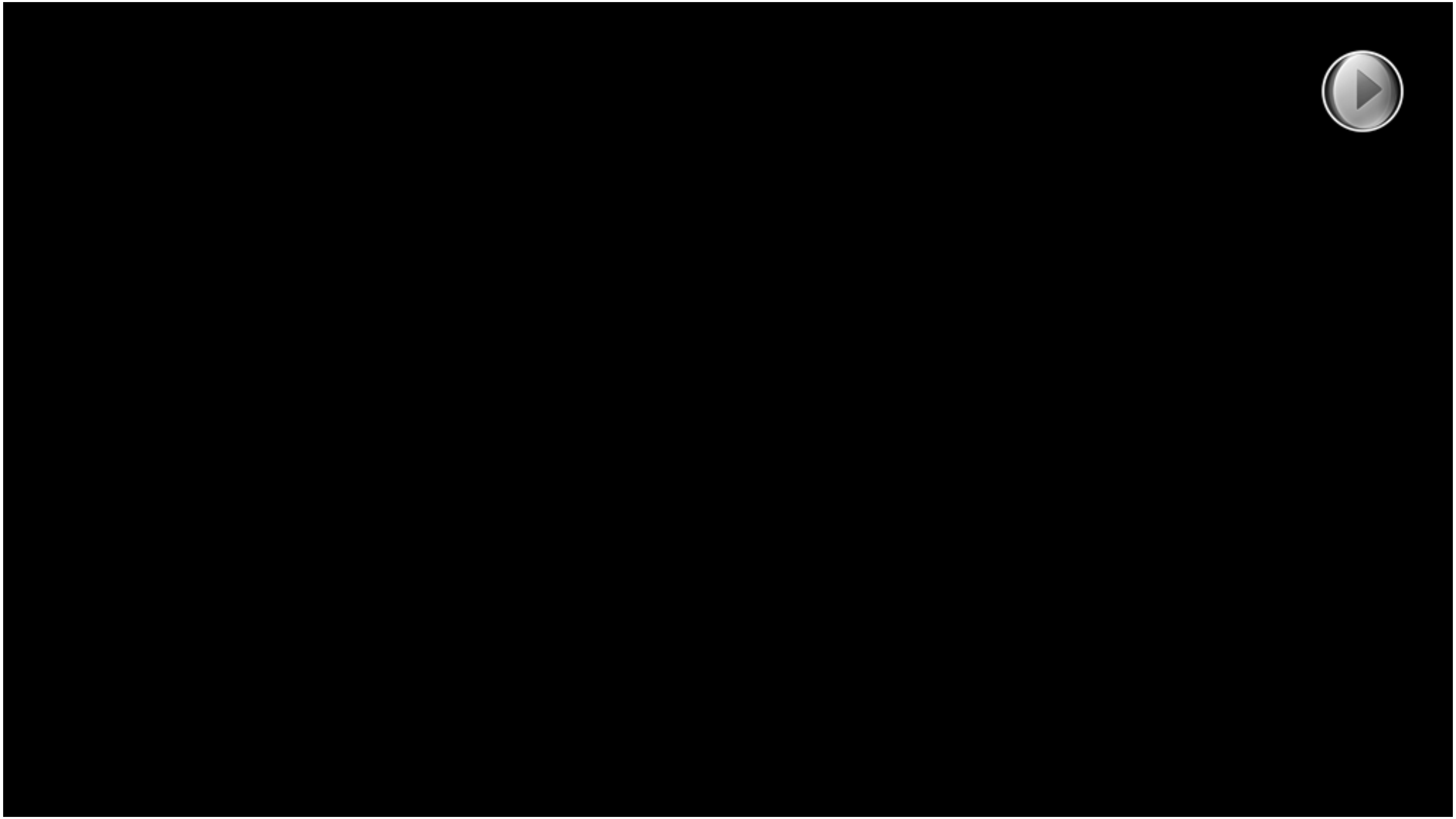
- Produce cold antihydrogen at the minimum of a multipolar, minimum-B trap

- Get rid of any remaining charged particles

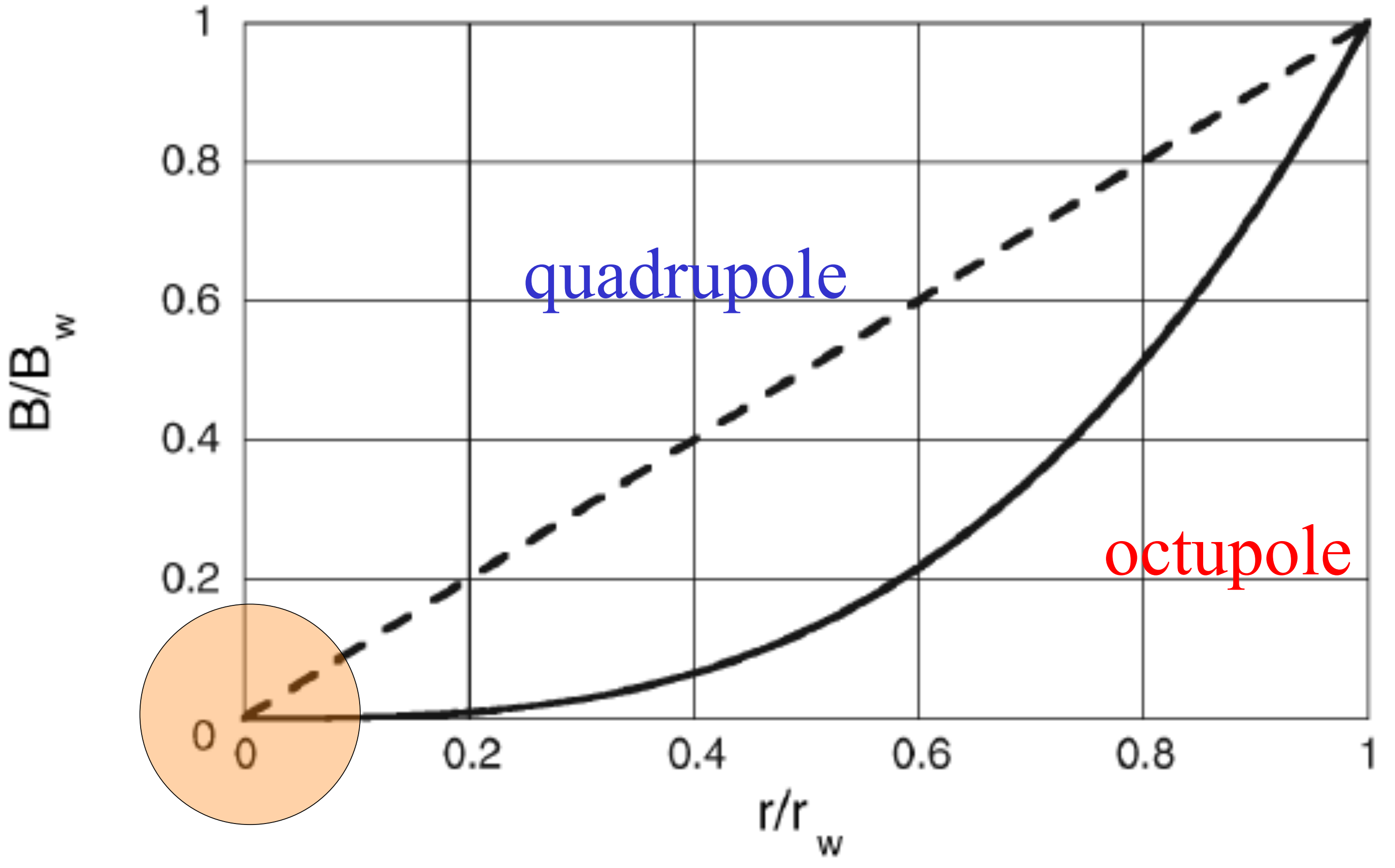
- Shut off the atom trap *as quickly as possible* to release any trapped antihydrogen

- Detect the antiproton annihilation from released antihydrogen with a *position sensitive annihilation detector*

- Use event topology to reject cosmic rays

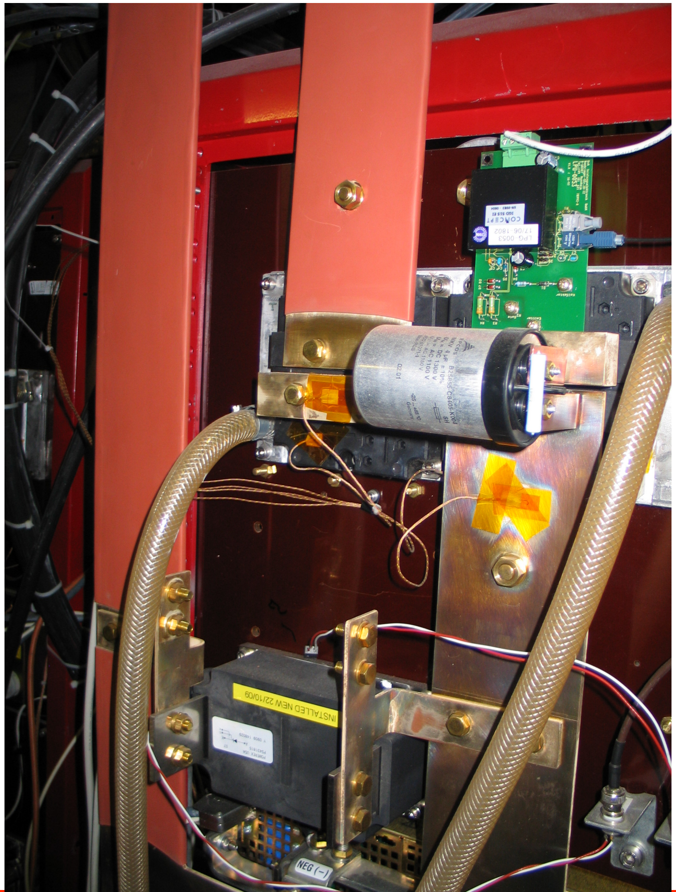


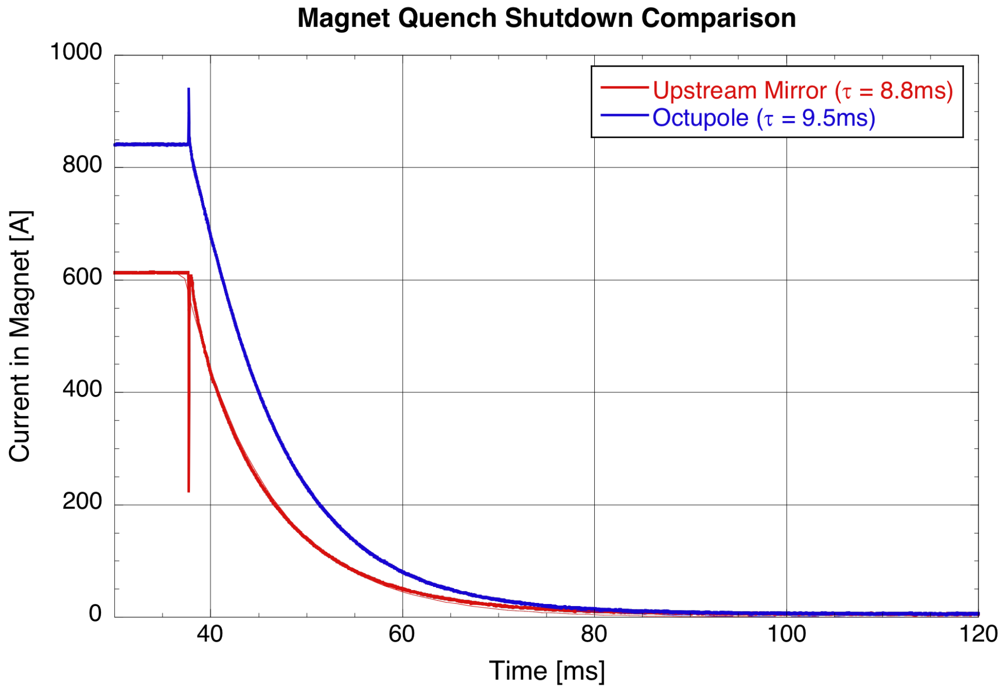
The ALPHA Approach: higher-order multipole



Detection of trapped antihydrogen: Rapid Shutdown

- Hardware patterned after G. Ganetis – IGBT switch to dump resistors
- Signal conditioning hardware from CERN LHC test chain
- Home-made FPGA QPS
- Taps on magnets, vapor cooled leads, and SC leads
- Magnets quench when shutting down – have survived several 10^3 cycles of this

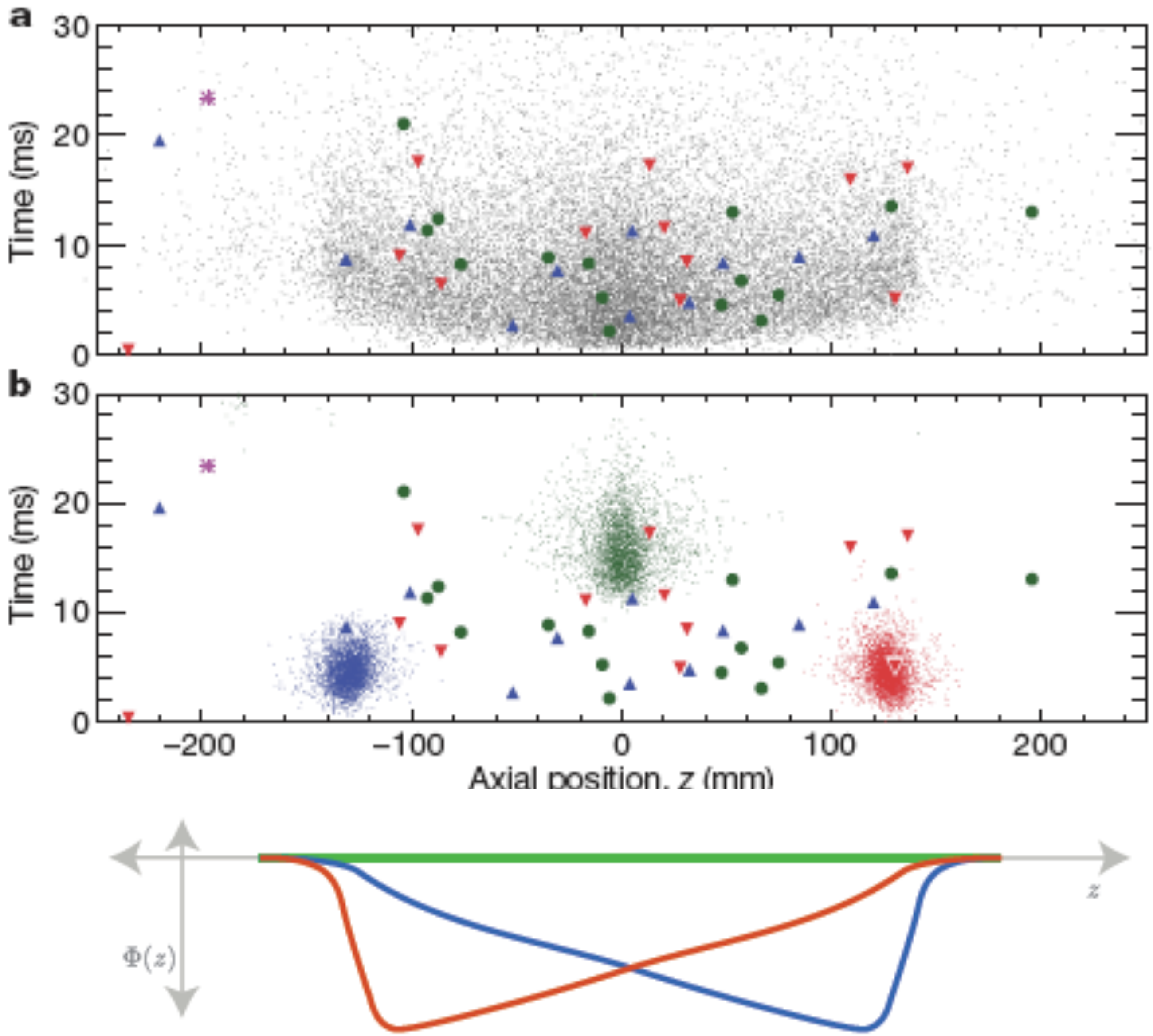




A kinder, more gentle ALPHA (2015)

- ‘Fast ramp down’ of magnets in atom trap
- Linear shutdown in 1.5 s
- Magnets don’t quench
- Smaller temperature rise in electrodes
- Avoid cryo recovery waiting time of about 7 minutes
- More experimental cycles per shift
- Made possible by improved background rejection routines using multivariate analysis (MVA)

The First Trapping Result (2010)



HBAR simulation

left bias
right bias
no bias

PBAR simulations

1 event with heated positrons

Some ALPHA Highlights (the original apparatus)

1. Demonstration of antihyrogen trapping: Andresen, G.B. *et al.*, Trapped Antihydrogen, *Nature*, **468**, 673 (2010).

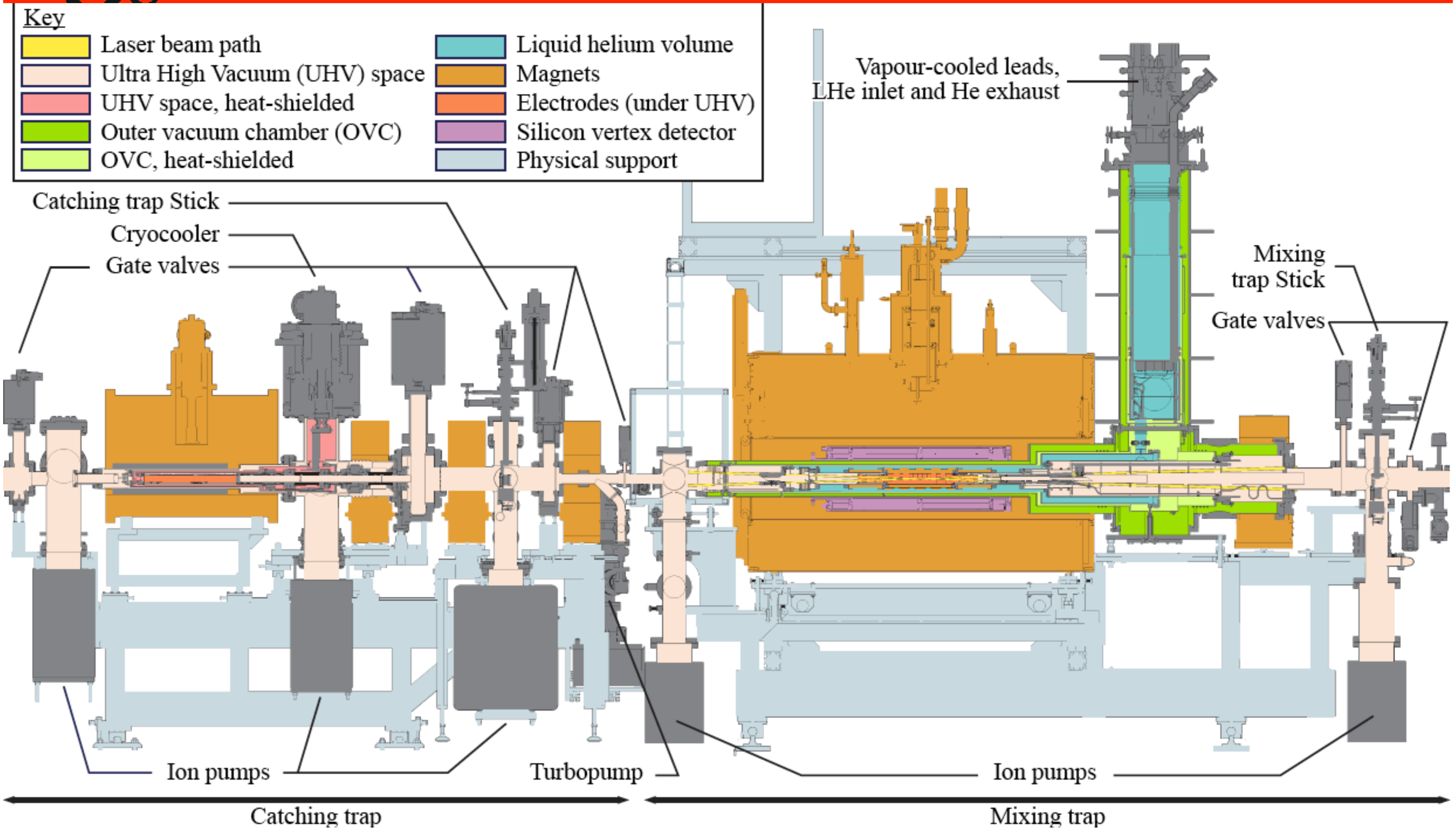
2. Long term storage of trapped antihydrogen:Andresen, G. B. *et al*. Confinement of antihydrogen for 1,000 seconds. *Nature Physics* **7**, 558 (2011).

3. Microwave induced spin-flip in trapped antihydrogen: Amole, C. *et al.,* Resonant quantum transitions in trapped antihydrogen atoms, *Nature* **483**, 439 (2012).

4. Gravity? Amole, C. *et al.*, Description and first application of a new technique to measure the gravitational mass of antihydrogen, *Nature Communications* DOI: 10.1038/ncomms2787 (2013).

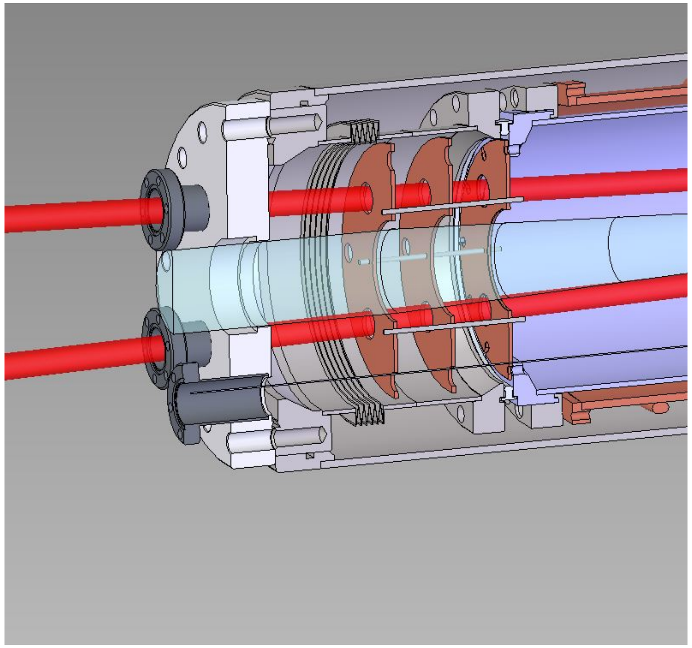
5. Test of neutrality: *An experimental limit on the charge of antihydrogen,* C. Amole *et al, Nature Communications* 5, 3955 (2014).

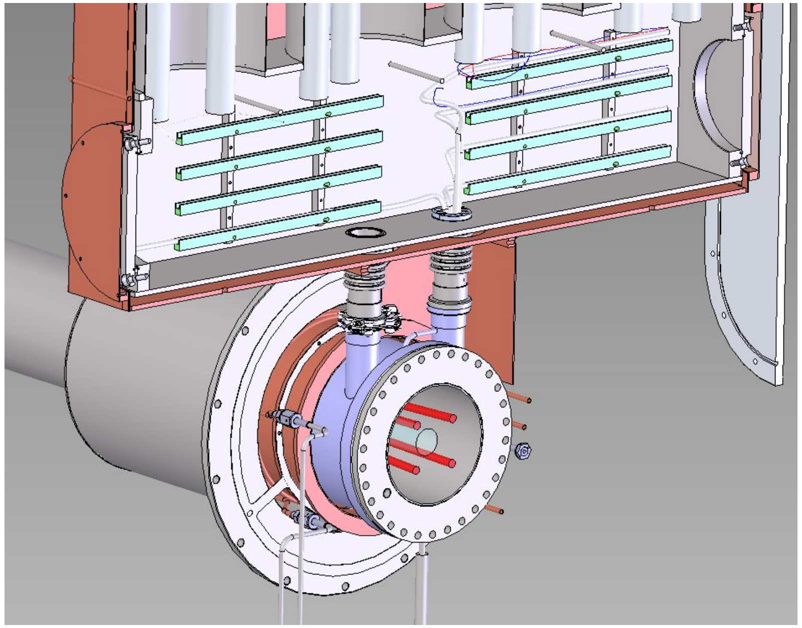
ALPHA-2

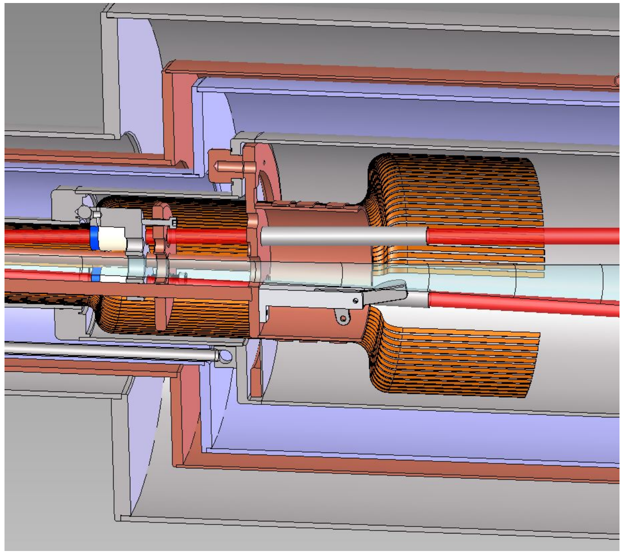


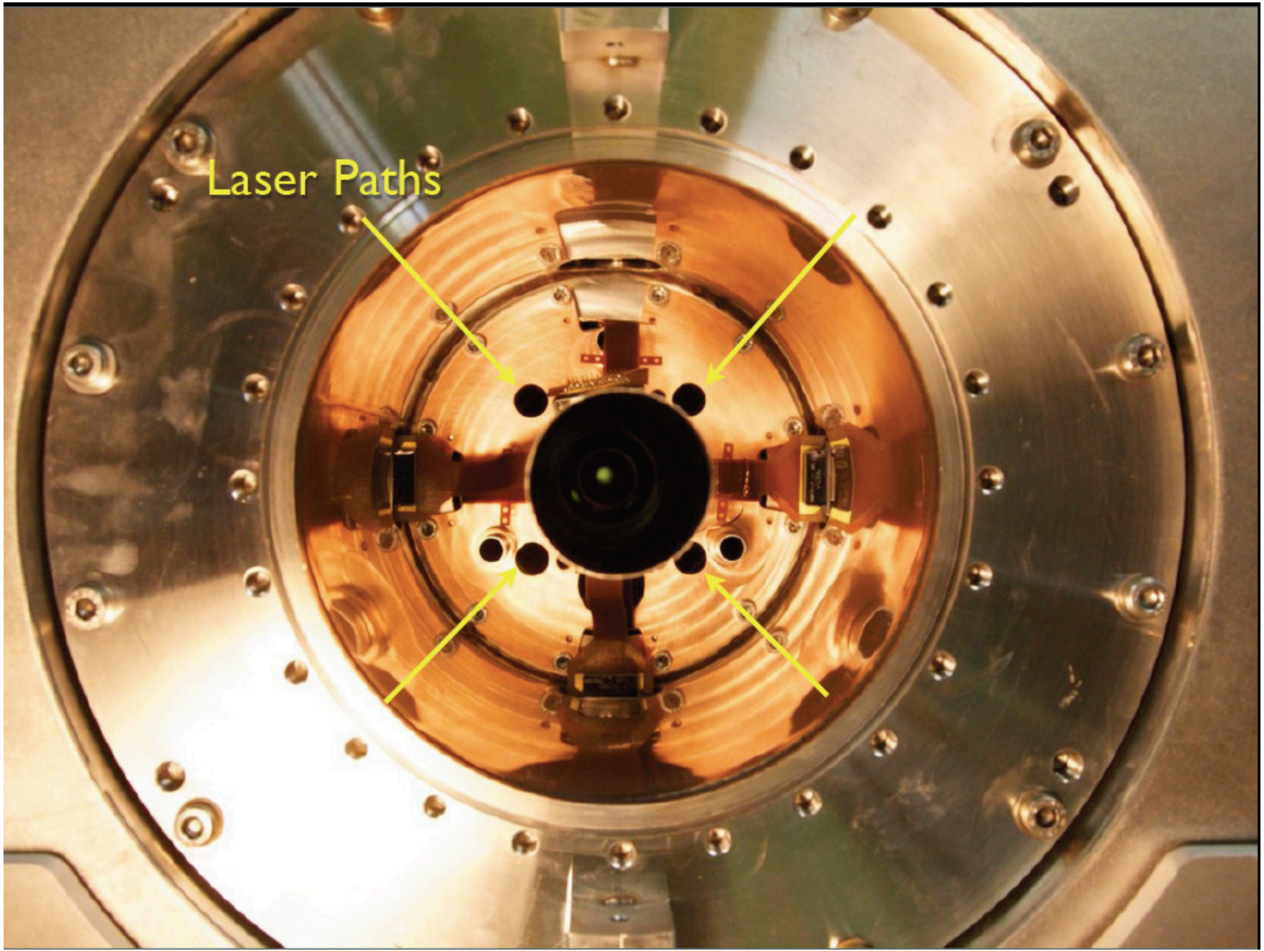
Key
Laser beam path
Ultra High Vacuum (UHV) space
UHV space, heat-shielded
Outer vacuum chamber (OVC)
OVC, heat-shielded
Liquid helium volume
Magnets
Electrodes (under UHV)
Silicon vertex detector
Physical support
Vapour-cooled leads, LHe inlet and He exhaust
Catching trap Stick
Cryocooler
Gate valves
Mixing trap Stick
Gate valves
Ion pumps
Turbopump
Ion pumps
Catching trap
Mixing trap

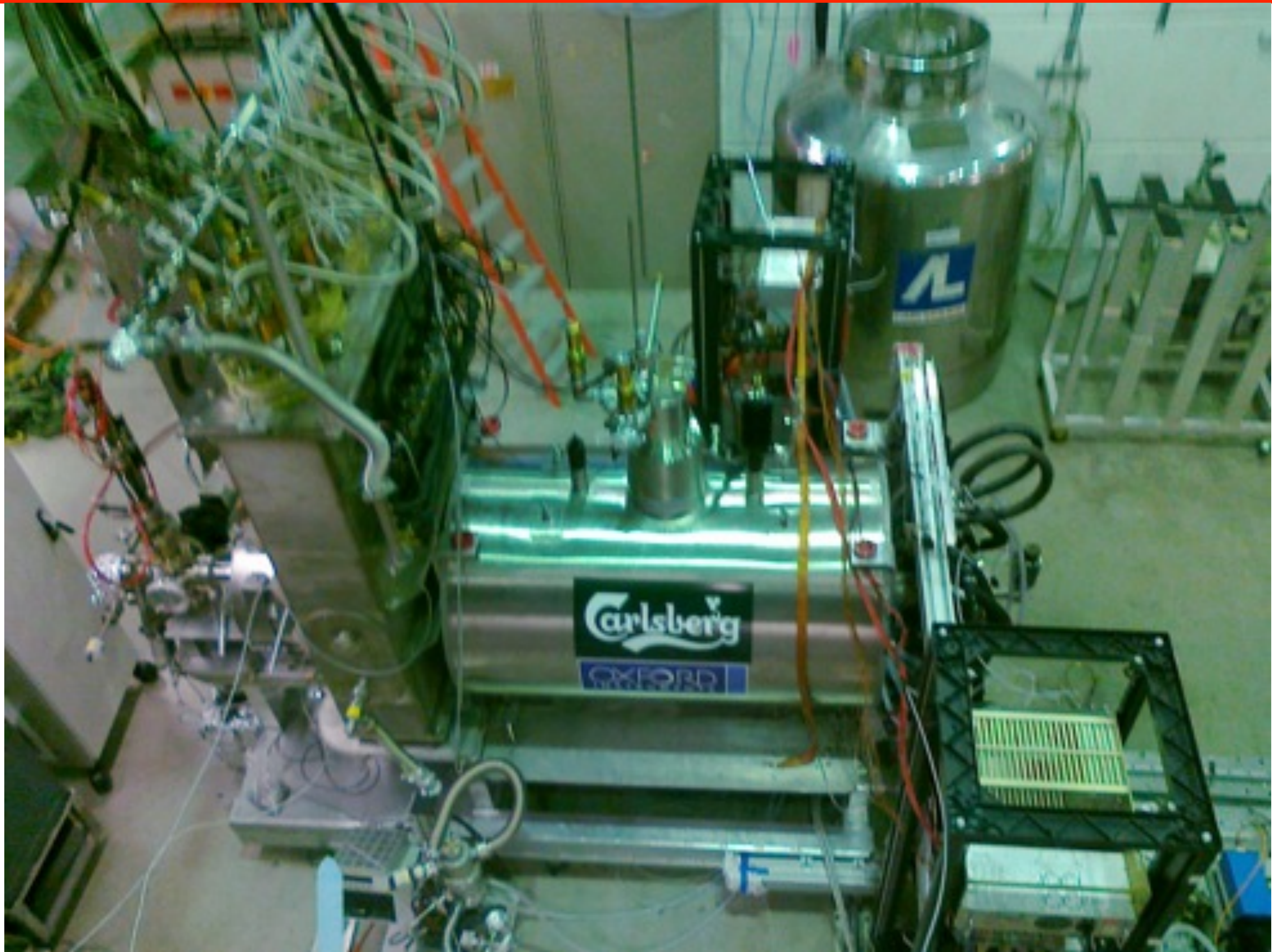
LASERS!

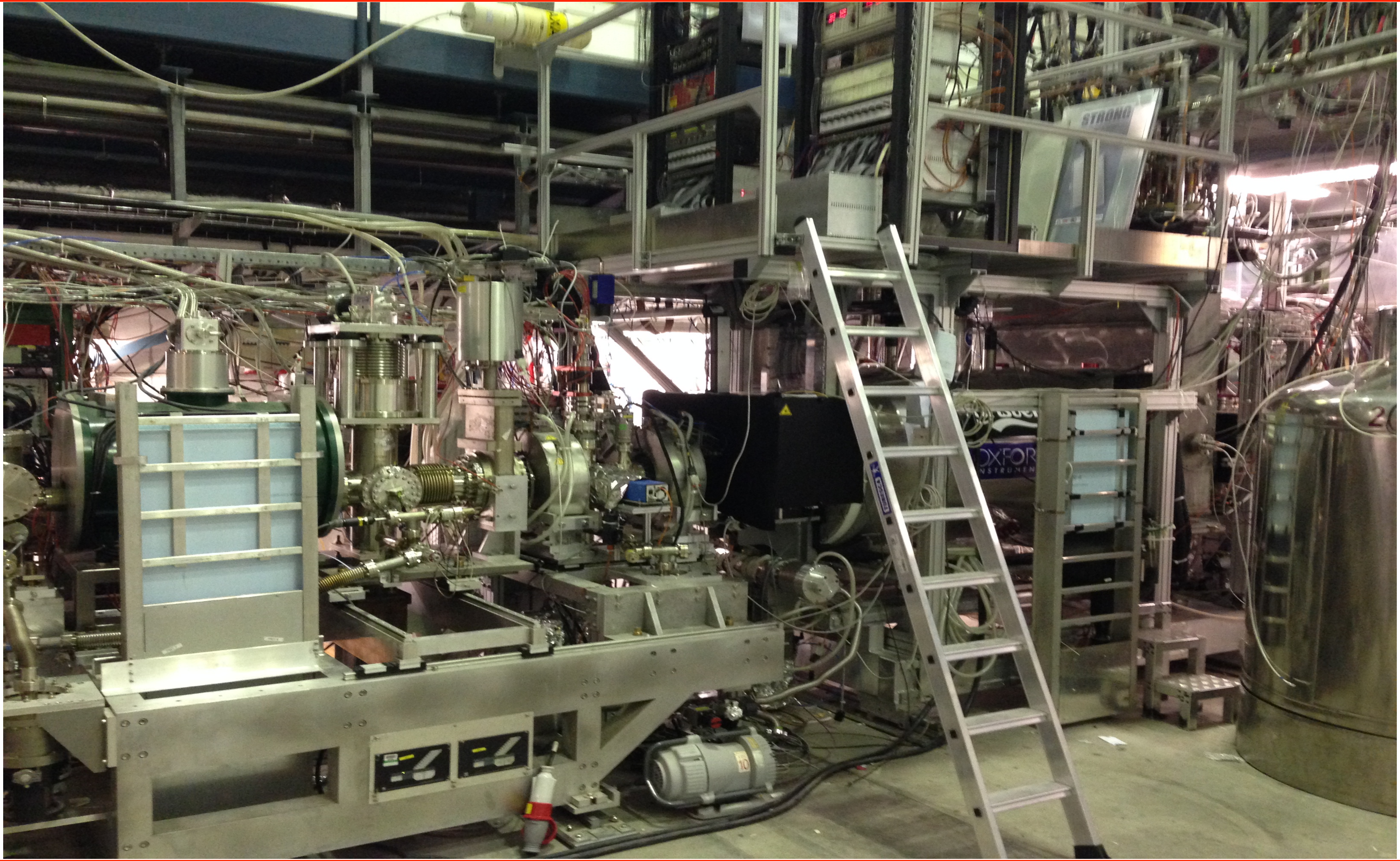






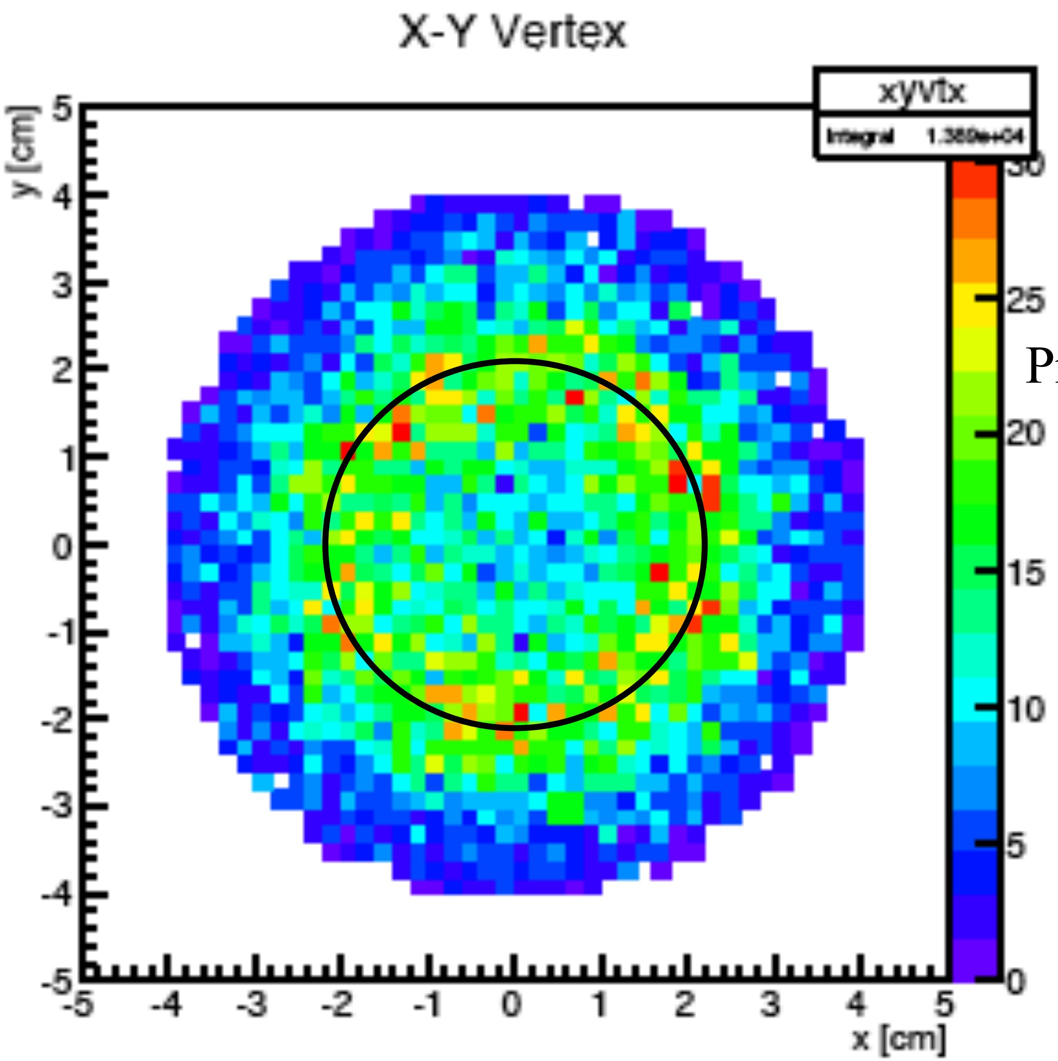

Laser Paths


Carlsberg
OXFORD



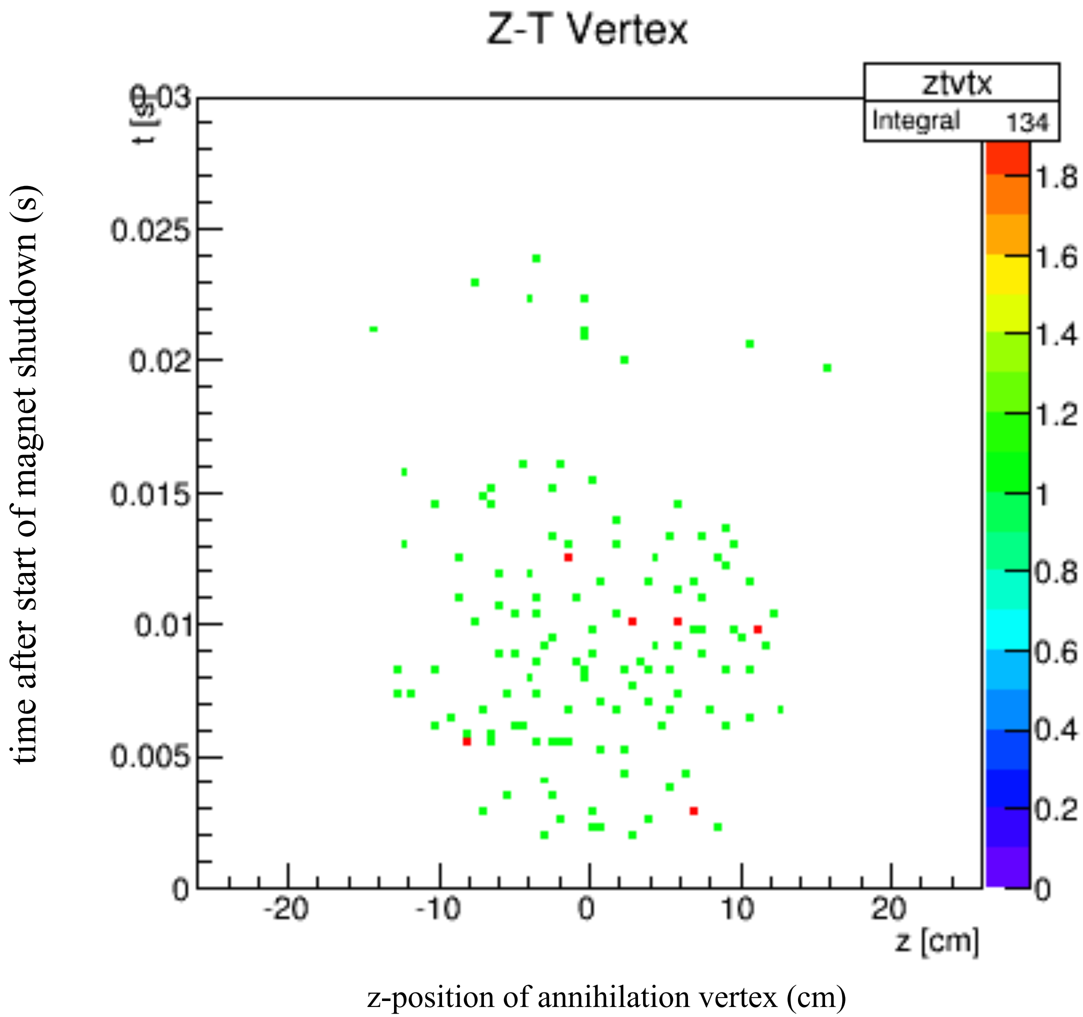
ALPHA-2 Timeline

- March 2012 – decision to remove original ALPHA from the zone
- June 2012 – pbars caught in ALPHA – 2 catching trap
- December 2012 – pbars and positrons stored in ALPHA-2 atom trap
- 2013 – no beam
- November 2014 – trapped hbar in ALPHA-2
- December 2014 – 243 laser light overlapped with trapped hbar



Produce ~8000 hbar per trapping attempt

ALPHA-2 Released Antihydrogen Events - 2014 Run

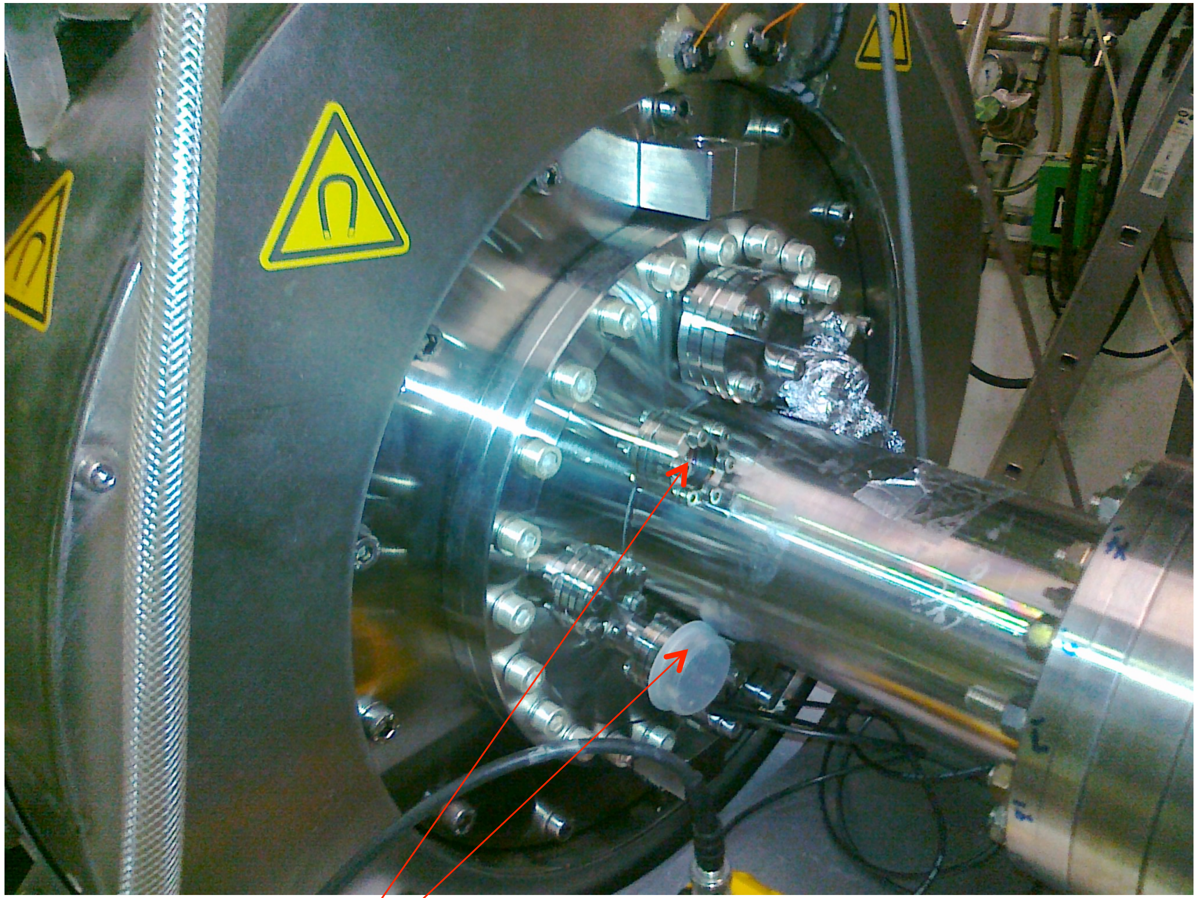


- ~140 events detected
- ~ 230 antihydrogen trapped
- Up to 2.4 atoms per attempt (shift averaged)
- Four attempts per hour
- Very fast commissioning – first events after six weeks of beam

Laser System 1s-2s

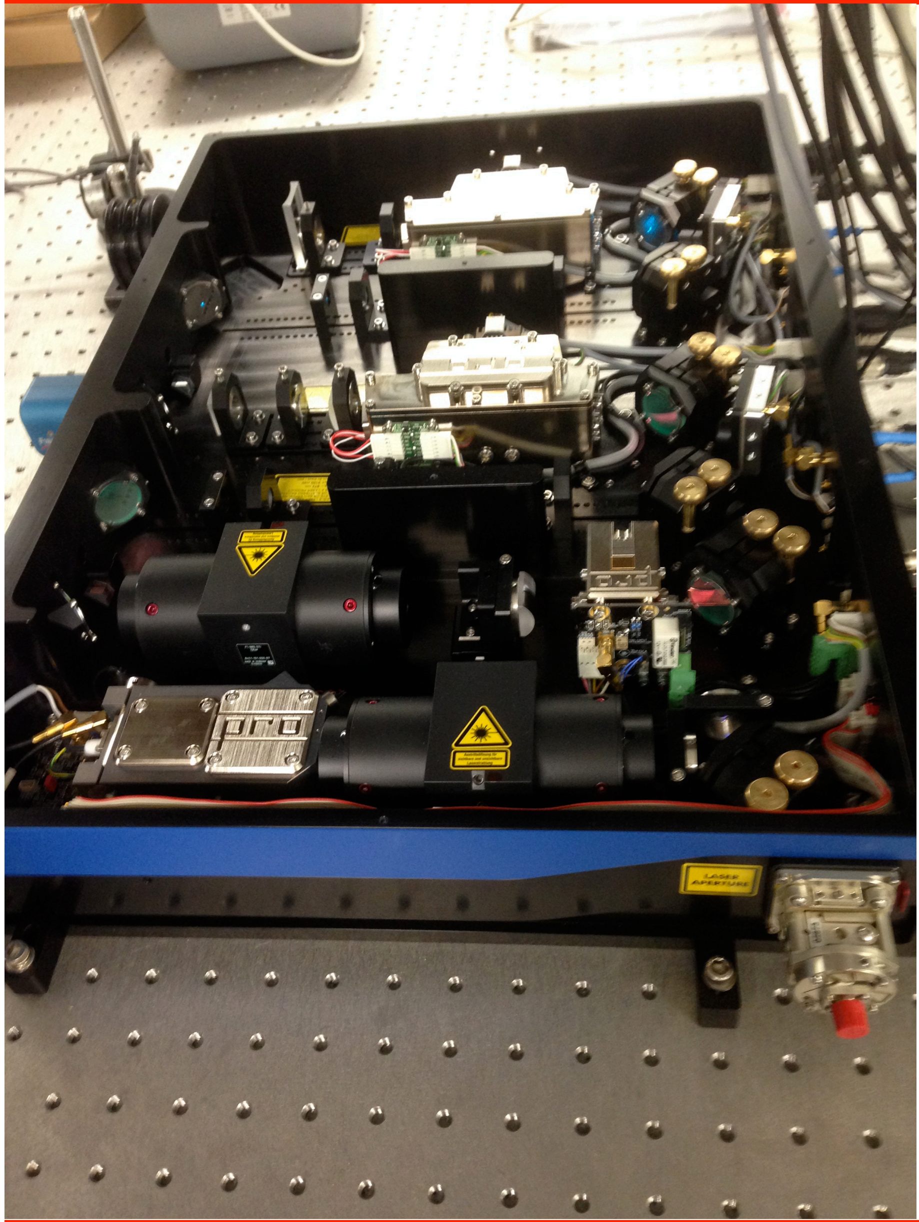
ERC Advanced grant (2.2 Meuro)

- Toptica laser, FHG, CW, >50 mW @ 243 nm
- Optical frequency synthesizer by Menlo systems
- External, environment-controlled, reference cavity by Menlo Systems
- Cryogenic optical resonant cavity in the ALPHA-2 cryostat



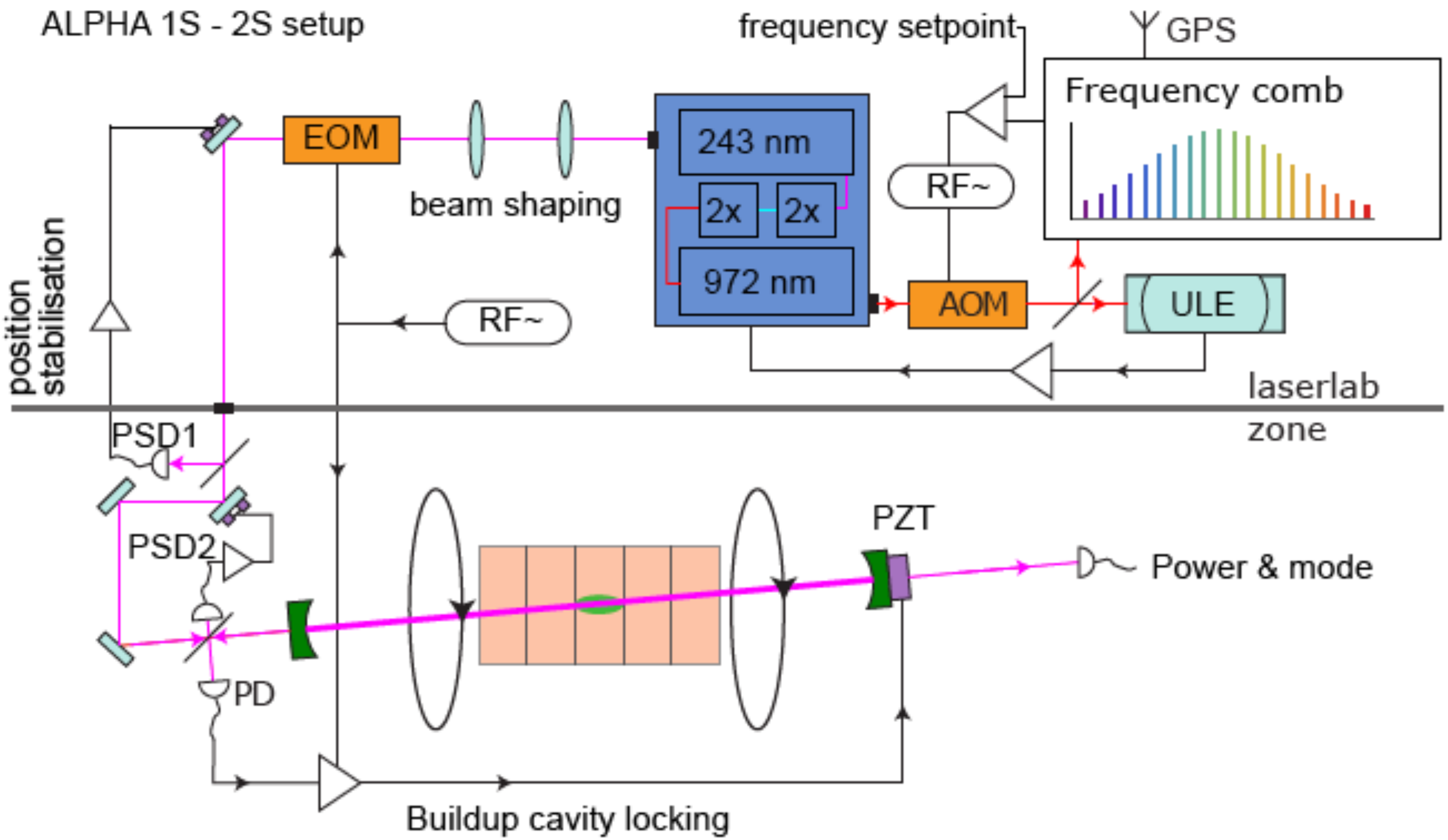
Laser windows

243 nm laser

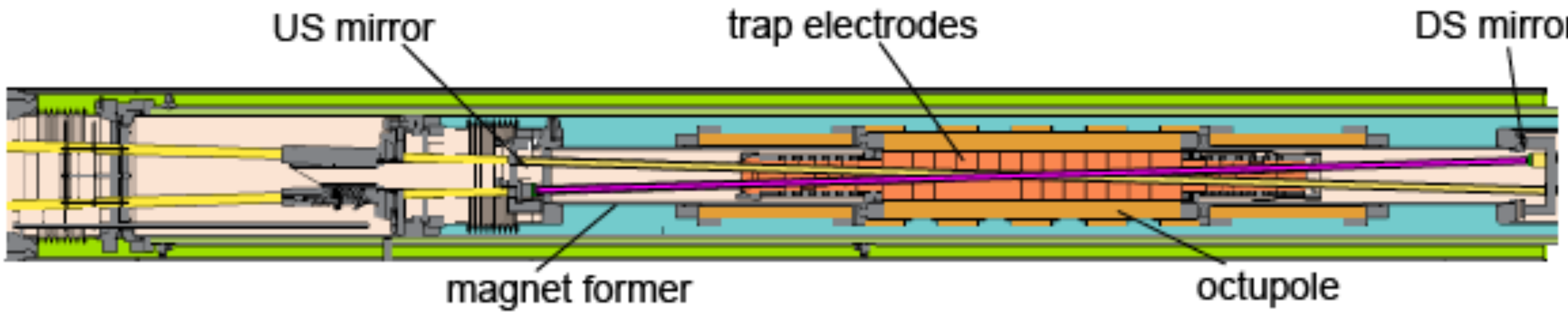


- All solid state, fourth harmonic generation
- > 50 mW indefinitely; easily makes 200 mW
- Limited by UV damage to optical elements
- Manufactured by Toptica

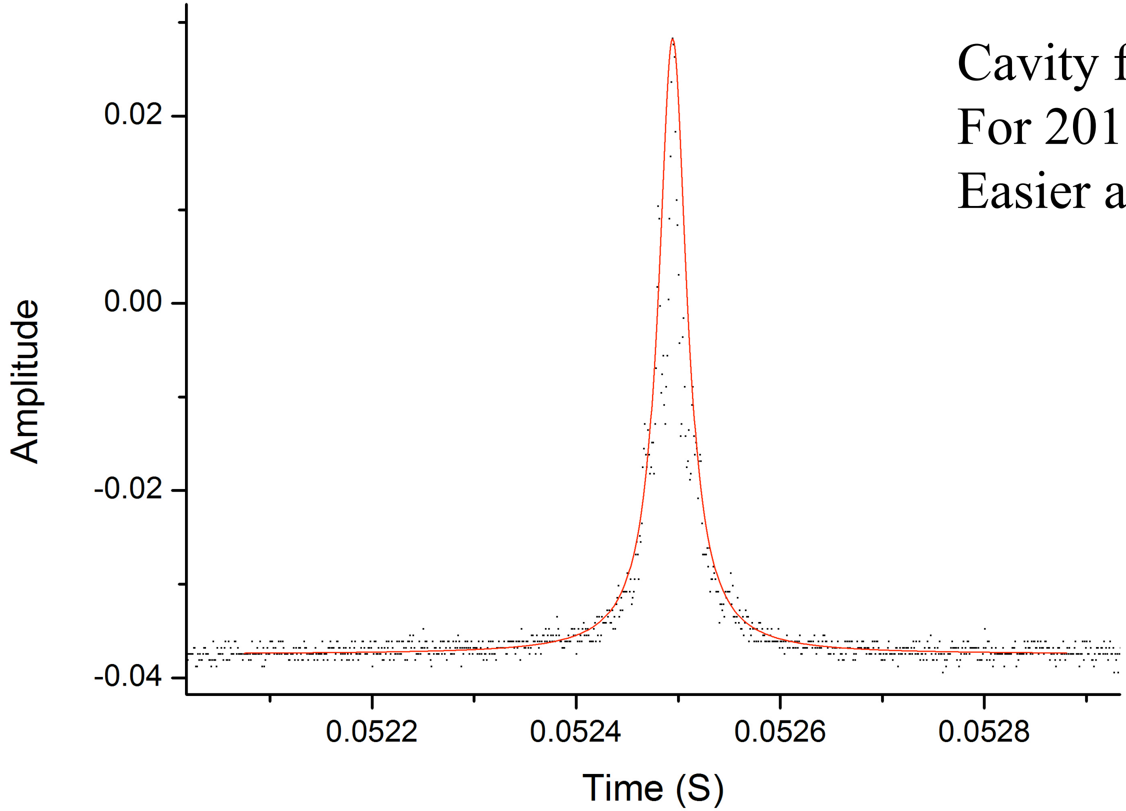
243 nm laser schematic



243 nm enhancement cavity geometry



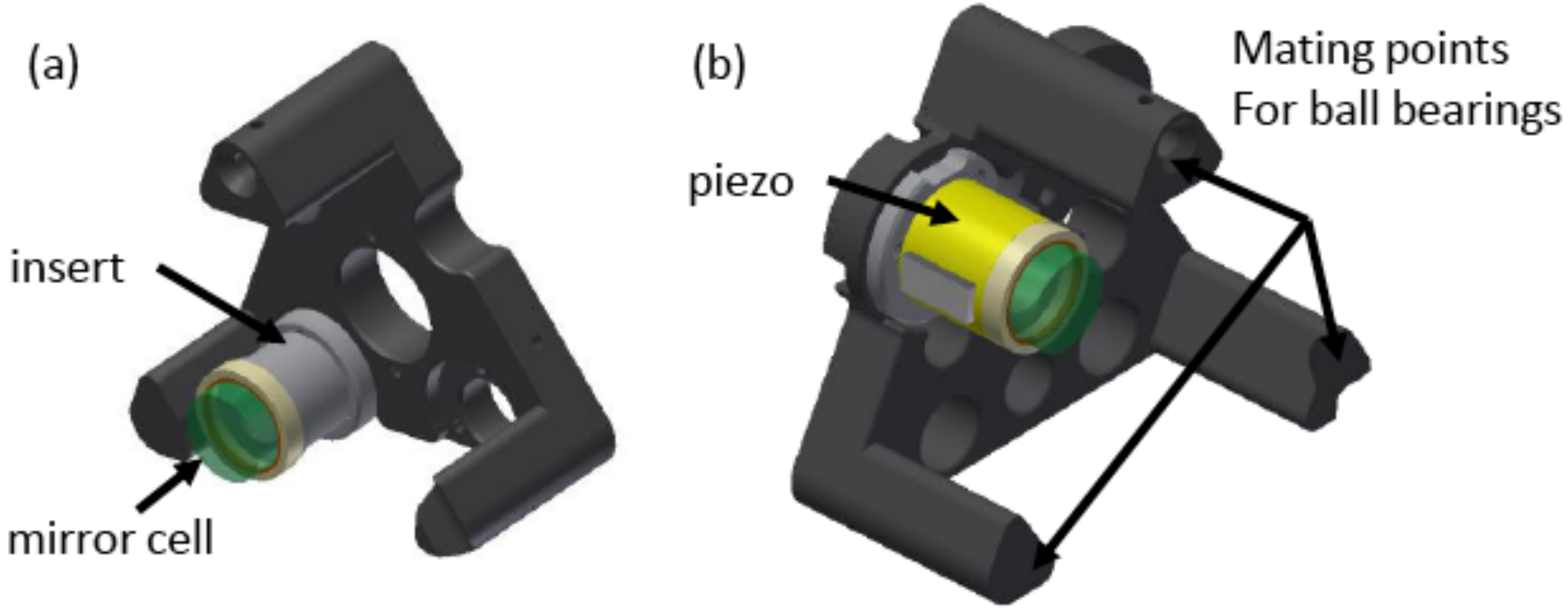
Cryogenic Buildup Cavity for 243 nm



Cavity finesse ~ 600
For 2016: two UV cavities
Easier access for modifcations

Laser scanned over longitudinal cavity resonance

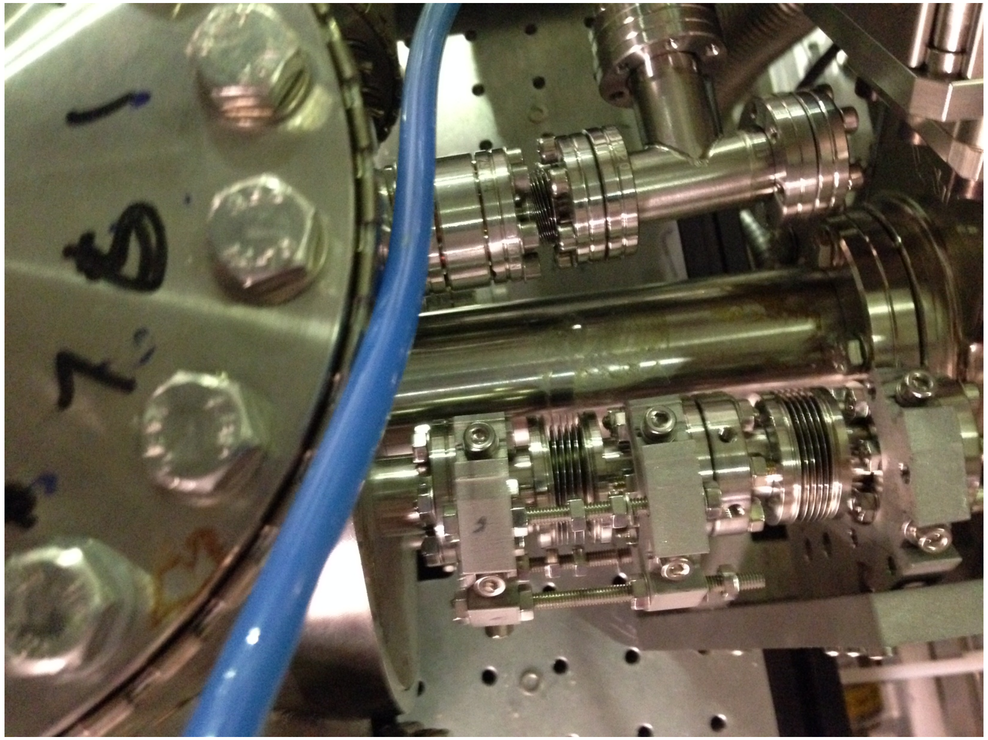
243 nm enhancement cavity geometry 2

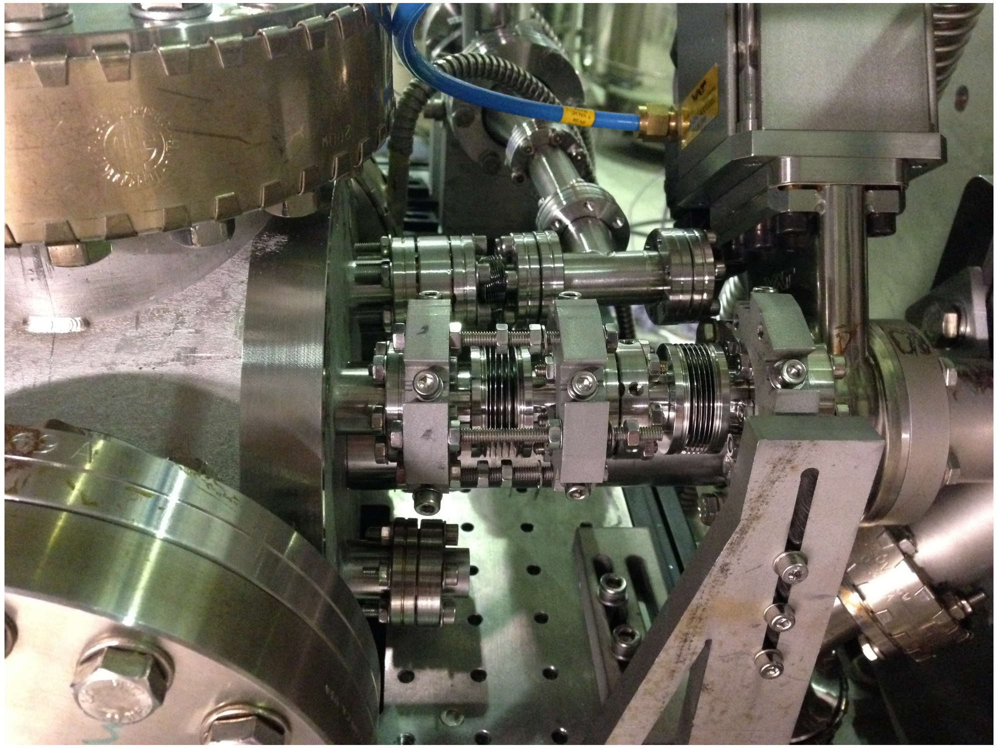


Cavity Mirror/Piezo Mounts

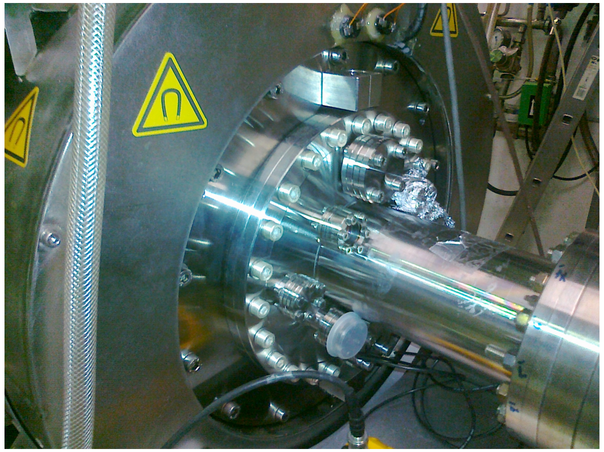
- DS mirror assembly failed on July 10th; later discovered to be a broken glue joint
- Survived six cooldowns and at least one bakeout; knew exactly when to fail

Plan B – rapidly constructed EXTERNAL cavity

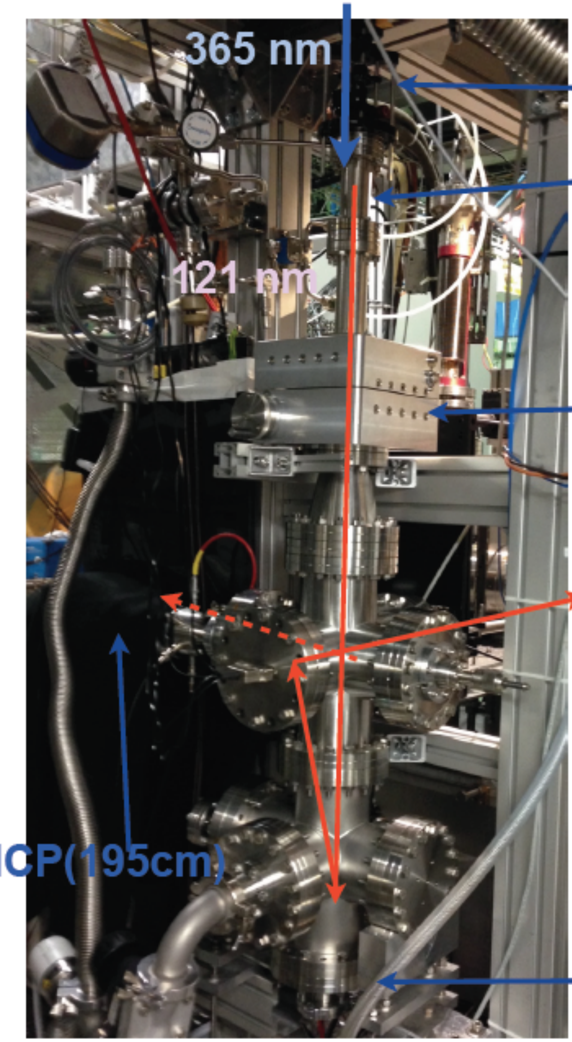




- Operational from early September
- 2.7 m length (90 cm internal cavity)
- Much more susceptible to vibration and temperature change
- Adjustable alignment
- Successfully and stably locked towards the end of the run
- Trials: 42 on-resonance; 39 off resonance; 12 no laser
- Estimate 650 mW power (50 mW laser)



Pulsed Lyman-alpha system

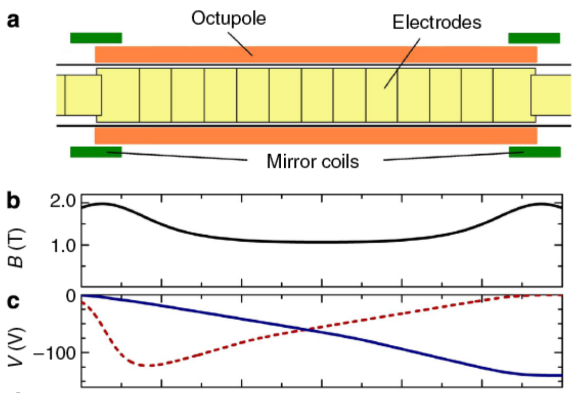


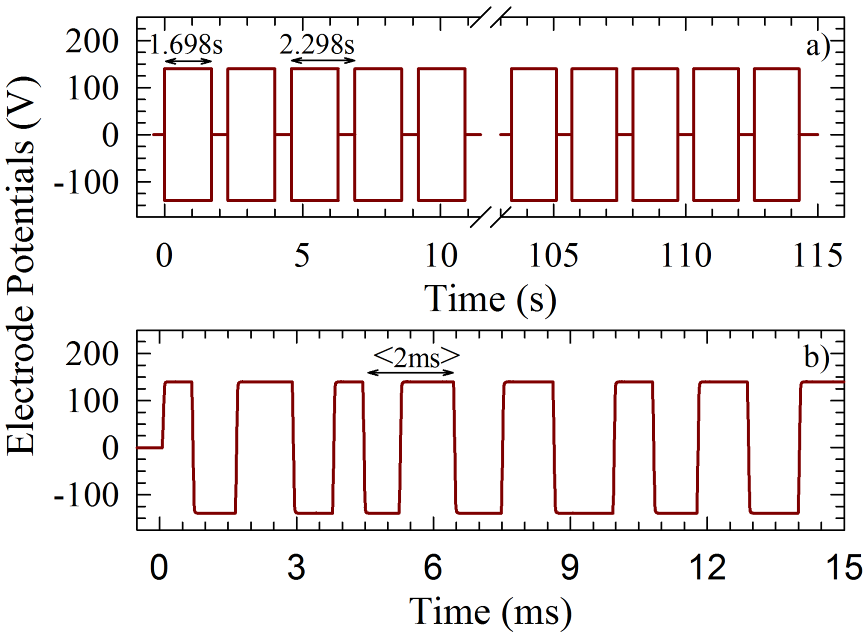
- Light generated and injected to the atom trap
- Working on alignment, beam exit
- Ready for 2016 run

Run Summary 2015

- Stable operation and antihydrogen trapping
- Essentially 100% utilisation of pbar shifts
- 24 hour cryogenic operation for the entire run – thanks to the cryo people for the hard work supplying helium to us
- Internal laser cavity failure very disappointing; external cavity successfully implemented, but with marginal power buildup
- Did multiple runs of realistic laser interaction measurements; de-bugged all of the essential operations
- Fully stabilised and referenced 243 nm laser system is operational; stably locked to internal or external cavity
- Progress with generation and injection of pulsed, Lyman-alpha light; should be fully operational in 2016 (spectroscopy, laser cooling)
- ALPHA-g device funded and design well underway

Antihydrogen Neutrality: Stochastic Heating of trapped particles

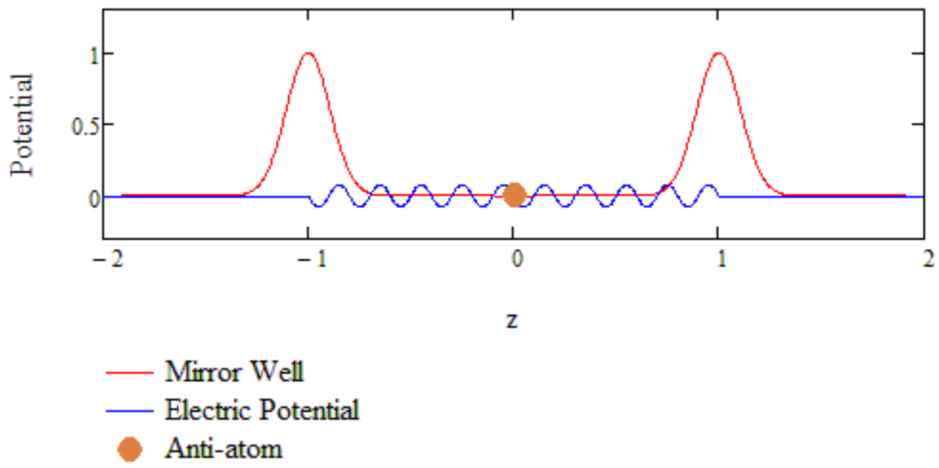




The basic idea: apply pulsed electric fields to the trapping volume when antihydrogen is trapped.

If the atoms are not neutral, they would eventually be removed by these electric fields.

Simple go - no go experiment; use simulations to help interpret result.



ALPHA

To be published in *nature*– tomorrow!

LETTER

OPEN

doi:10.1038/nature16491

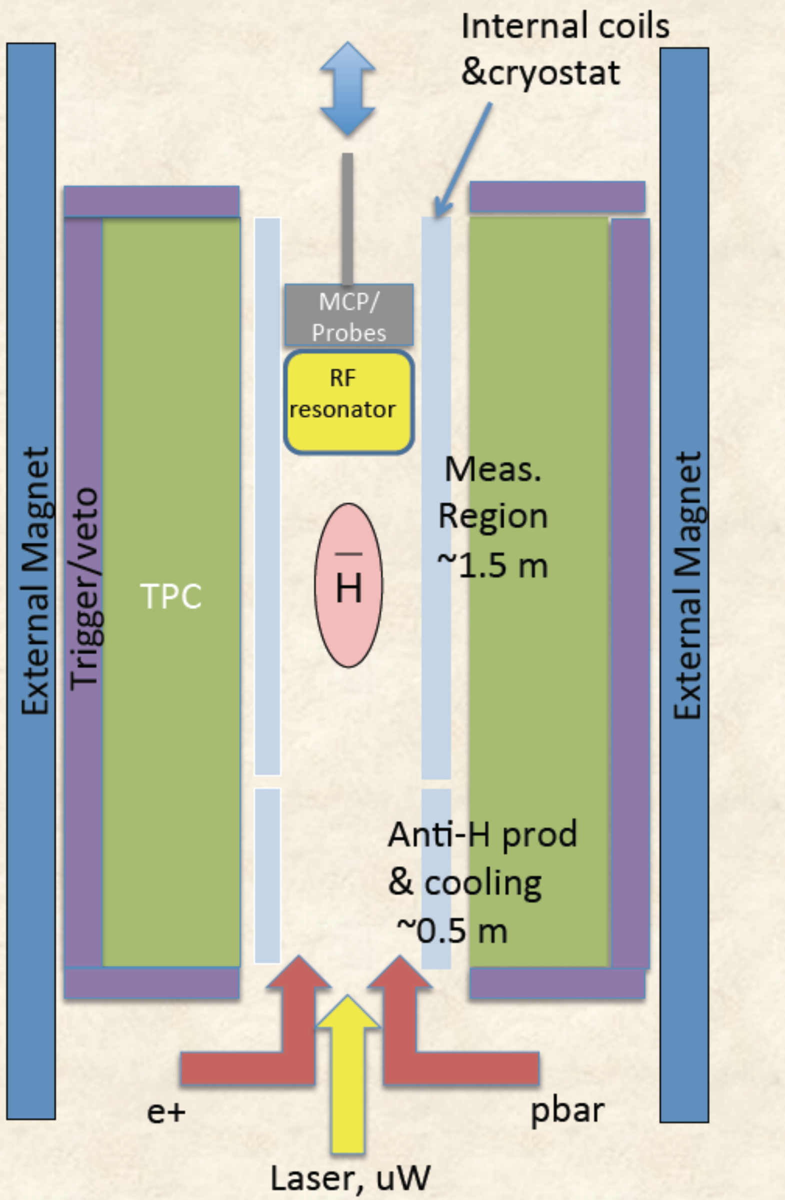
An improved limit on the charge of antihydrogen from stochastic acceleration

M. Ahmadi[1], M. Baquero-Ruiz[2,3], W. Bertsche[4,5], E. Butler[6,7], A. Capra[8], C. Carruth[2], C. L. Cesar[9], M. Charlton[10], A. E. Charman[2], S. Eriksson, L. T. Evans[2], N. Evetts[11], J. Fajans[2], T. Friesen[12], M. C. Fujiwara[13], D. R. Gill[13], A. Gutierrez[11], J. S. Hangst[12], W. N. Hardy[11], M. E. Hayden[14], C. A. Isaac[10], A. Ishida[7], S. A. Jones[10], S. Jonsell[15], L. Kurchaninov[13], N. Madsen[10], D. Maxwell[10], J. T. K. McKenna[13], S. Menary[8], J. M. Michan[13], T. Momose[16], J. J. Munich[14], P. Nolan[1], K. Olchanski[13], A. Olin[13,17], A. Povilus[2], P. Pusa[1], C. Ø. Rasmussen[12], F. Robicheaux[18], R. L. Sacramento[9], M. Sameed[10], E. Sarid[19], D. M. Silveira[9], C. So[2], T. D. Tharp[12], R. I. Thompson[20], D. P. van der Werf[10], J. S. Wurtele[2,21] & A. I. Zhmoginov[2]

ALPHA-g: What is it?

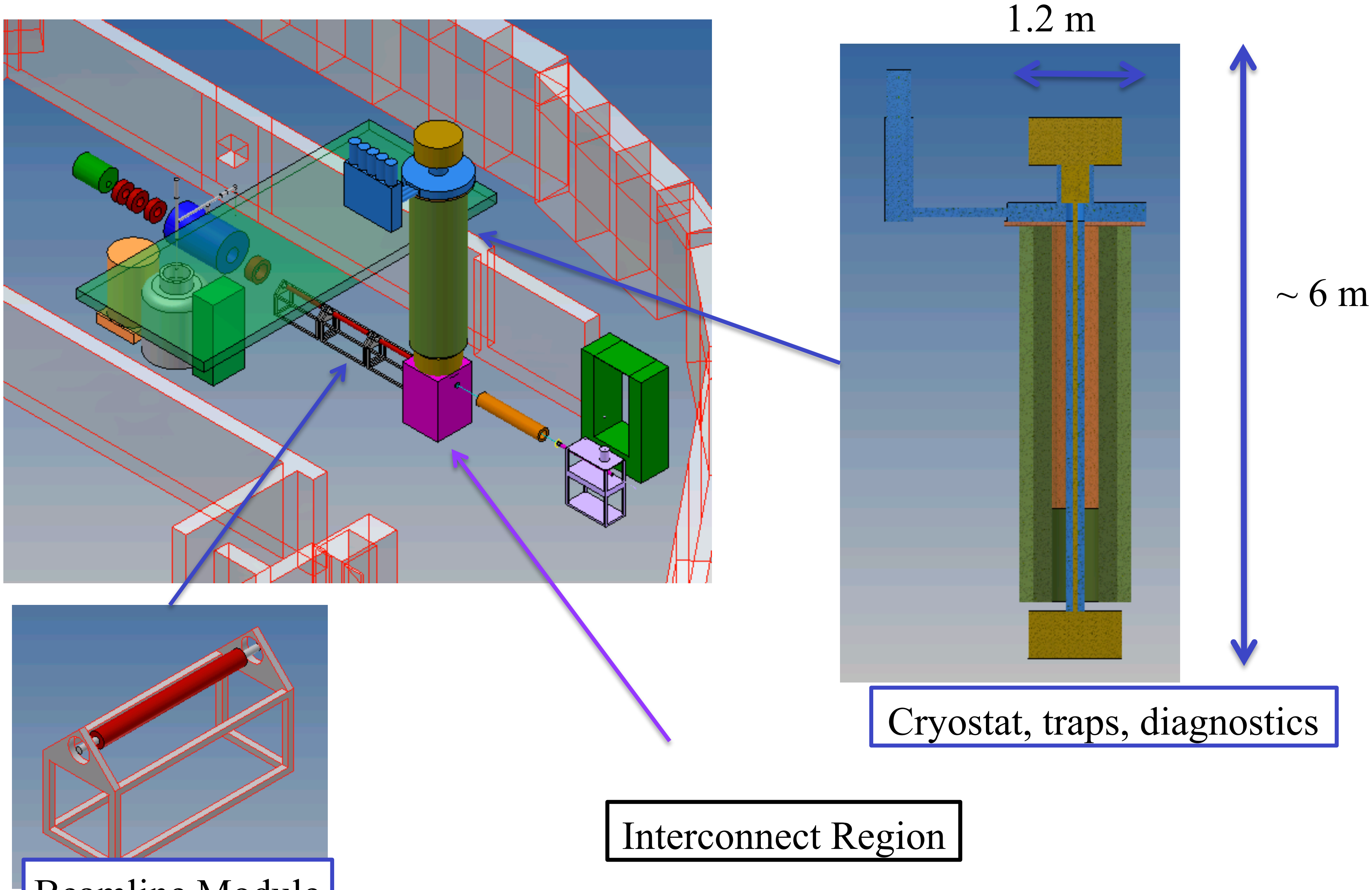
- A new approach to antimatter gravitation using techniques developed and demonstrated in ALPHA and ALPHA-2
- Addition of a VERTICAL atom trap to the existing ALPHA beamline
- Simple experimental concept: trap anithydrogen atoms, release them, see where they go and annihilate
- Use existing ALPHA-2 catching trap and positron accumulator
- New external solenoid; new superconducting atom trap, new annihilation detector (TPC)
- Funded by Canada fund for Innovation and the Carlsberg Foundation; others underway
- Physics goals: sign of g-bar; magnitude of g-bar to 1%
- First operation with particles: mid 2017

HOW: the ALPHA-g concept

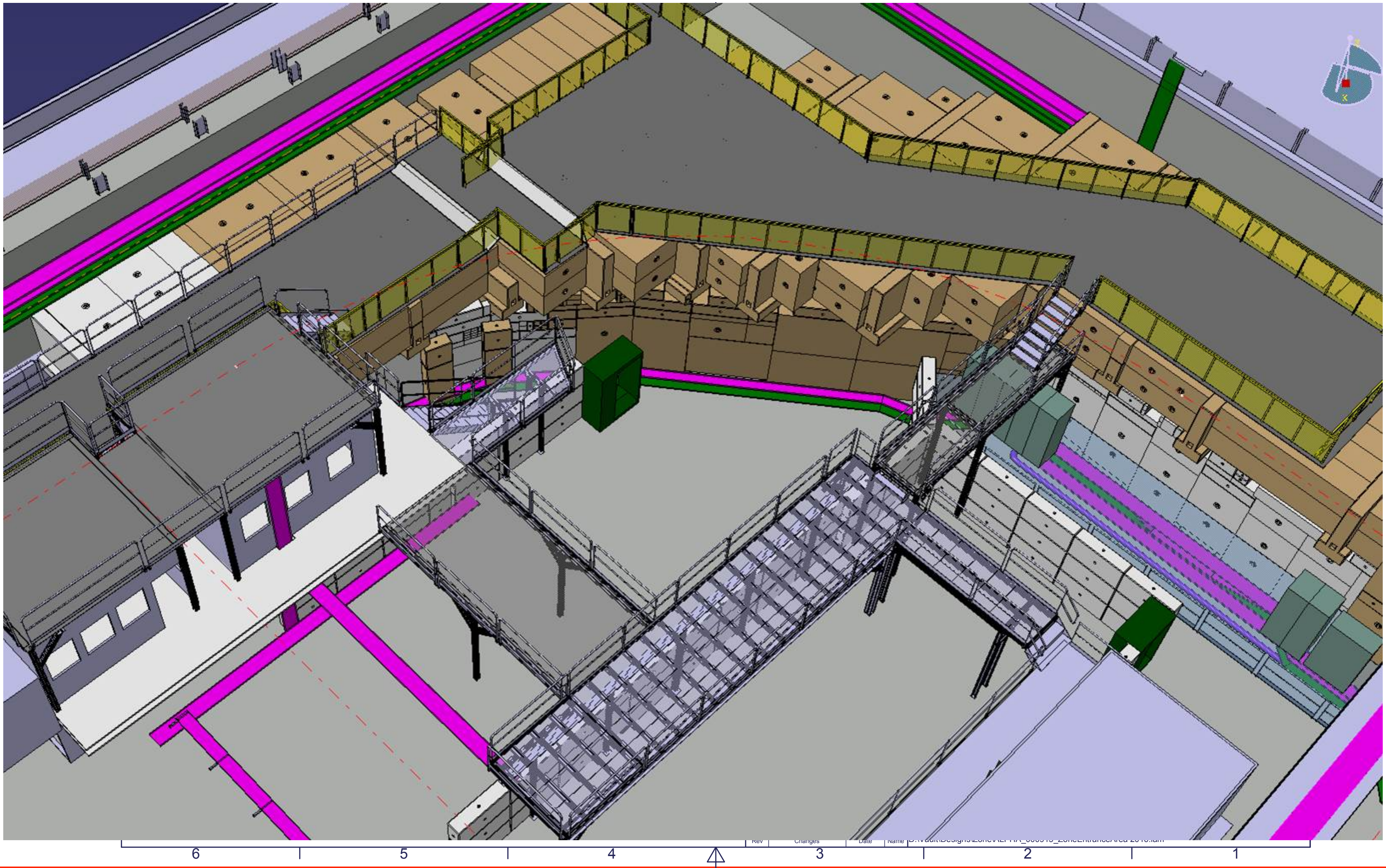


- Because spectroscopy isn't hard enough...
- Trap some hbar; drop it, see where it goes
- Measure the sign of g-bar (~ 1 month of beam)
- Measure the value of g-bar to 1% (4-5 years)
- Concept fully demonstrated in ALPHA – for horizontal geometry
- Funding from Canada (CFI), DK (Carlsberg

ALPHA-g Layout



ALPHA Zone Extension (F. Butin)



Thanks!

- To the AD team and CERN support groups (transport, workshops, etc.)
- To BASE for generous beam sharing
- To the cryo team for reliable helium supply under pressure
- To the SPSC (Claude, Magda, Xavier)for getting involved in the helium distribution project for the AD

How to get money from a beer company…

ALPHA rocks…