Addendum to the ALPHA Proposal

The ALPHA-g Apparatus

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Introduction

We propose to construct an extension to the ALPHA-2 apparatus. The purpose of this extension is to study the gravitational behaviour of antihydrogen atoms in the field of the Earth. In essence, we will build a vertical version of the ALPHA antihydrogen trap[1], the only device that has demonstrated reproducible trapping of antihydrogen atoms. The experimental strategy is conceptually simple: trap antihydrogen atoms, release them in a controlled fashion, and determine their fate using a tracking vertex detector that records the antiproton annihilation when the antihydrogen hits the walls of the apparatus. This work grows out of our earlier demonstration[2] of the controlled release of antihydrogen atoms in the original (horizontally oriented) ALPHA machine. In this proof of principle experiment, we described in detail how trapped antihydrogen could be used to study gravitation, and we explored many of the systematic effects that will need to be addressed. Our collaboration has extensive experience studying trapped antihydrogen and has produced numerous breakthrough results in recent years[3,4,5,6]

The new, vertical, atom trap, known as ALPHA-g, will share the ALPHA experimental zone in Building 193. An extension to the physical area of the zone has been conditionally approved by the Experimental Physics Department and would be constructed at the end of the 2016 beamtime. The existing ALPHA-2 catching trap for antiprotons and the ALPHA positron accumulator will be used to provide antiprotons and positrons to the vertical antihydrogen trap. The main new investments in equipment are a large bore, vertical solenoid magnet for the Penning trap field, superconducting magnets for the vertical atom trapping regions, a large volume Time Projection Chamber (TPC) detector for vertex detection of antiprotons, and the beam transport sections to connect the vertical machine to existing ALPHA infrastructure. These investments are already fully funded by new grants from The Carlsberg Foundation, the Canada Fund for Innovation, and the Canadian provinces of Alberta, British Columbia, and Ontario. The other ALPHA institutes are expected to contribute hardware and operational funds as per the original ALPHA Memorandum of Understanding. Our goal is to have the new equipment installed at CERN by the autumn of 2017.

Physics Goals

As the SPSC has already approved two experiments for the study of gravitational behaviour of antimatter, we will not repeat any of the motivations for these fundamental and potentially revolutionary measurements here. We would rather like to point out that the unique feature of ALPHA-g is that all of the techniques needed to study antimatter gravity in this machine *have already been demonstrated by our collaboration.* We will utilise the proven methods of cold antihydrogen synthesis and trapping that have been developed and exploited in the ALPHA and ALPHA-2 traps. We rely on no unproven or speculative techniques or technologies for our initial success. Our extensive experience with antihydrogen synthesis, trapping and detection allow us to have ambitious physics goals and realistic estimates of our future capabilities. Ours is the only *demonstrated* experimental approach to address the gravitational behaviour of antimatter.

We propose a two-phase program for the study of antimatter gravitation. Each phase has well-defined, quantitative goals.

Phase one: gravity or antigravity?

This phase of the program will endeavour to determine the *sign* of the gravitational force between matter and antimatter, *i.e.,* is the force attractive or repulsive? The technique for making this determination is very simple in principle; one releases the trapped, cold (<500 mK) anti-atoms and measures the position at which they annihilate when they meet the walls of the atom trap. Studying the vertical distribution of annihilation events on a position sensitive annihilation detector allows one to put limits on the strength of the gravitational force they experience. Obviously, colder atoms provide greater sensitivity to gravitational effects. We initially explored this technique by analysing release data from the original ALPHA machine[2] - although the experiments done to produce the data did not anticipate and were in no way optimised for a gravity study. Using the data collected in the horizontally oriented ALPHA device, we could not determine the sign of the gravitational force, but we could demonstrate the potential for this innovative technique. More detail is provided below. Our goal is to commission the ALPHA-g apparatus and perform this measurement before the beginning of the long shutdown (LS2) in 2018.

Phase two: more precise measurement of *g-bar:*

The second phase of the experiment would refine the release measurements to determine the magnitude of the gravitational acceleration to higher precision – looking for even a slight deviation between matter and antimatter. Current simulations suggest we can determine the magnitude of *g-bar* to one per cent or better. See below for more detail. These measurements would eventually include Lyman-alpha laser cooling of trapped antihydrogen, currently being developed in ALPHA-2. This phase of the program would commence after LS2 and involve some modifications to the Phase 1 apparatus.

Overview of the ALPHA-g apparatus

The ALPHA-g experiment consists of a vertically oriented magnetic atom trap with a Penning-Malmberg plasma trap for use in the production and trapping of antihydrogen. Sequencing of the magnetic traps along with a central magnetic analysis region is designed to achieve an initial up/down measurement of antimatter gravitation and ultimately a 1% measurement on antimatter gravitation g (see the following section).

Conceptual design of the cryostat, internal penning traps, trap magnets and diagnostics has been conducted across the ALPHA collaboration. Major mechanical design for the cryostat, support structure, and mechanical elements of the beamline, as well as oversight on their construction and project management is being conducted by the Technology Division of STFC in the UK. The execution of the internal trap superconducting magnets is underway by BNL in the USA (see below).

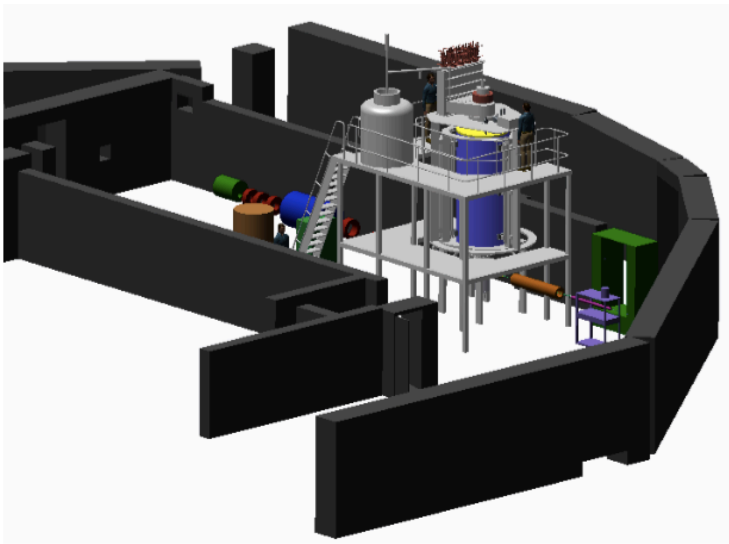


Figure 1: Overall layout of ALPHA-g in the expanded ALPHA experimental zone
The ALPHA-2 catching trap (green solenoid, upper left) atom trap (blue solenoid) and transfer magnets (short red solenoids) are illustrated to the left of the ALPHA-g superstructure. The existing positron accumulator (brown solenoid, purple source module) is to the right. The vertical ALPHA-g solenoid (blue) is 3m in length. The liquid helium dewar on the platform feeds the cryostat tower, containing the HTS current leads for powering the magnets.

The ALPHA-g traps will reside in a vertical cryostat situated on the beamline in the existing ALPHA zone (Figure 1). The main ALPHA-g support structure includes the cryostat around which a 1 T warm-bore vertical solenoid will be supported. This solenoid, as in ALPHA-2, is being designed by Oxford instruments in the UK. The radial time projection chamber detector (TPC) (see below) will be supported in the radial space between these two structures. Beneath the cryostat, new magnetic beamlines consisting of a solenoid channels are designed to guide antiprotons and positrons into ALPHA-g, as well as to permit positrons to continue to be used with ALPHA-2 (Figure 2).

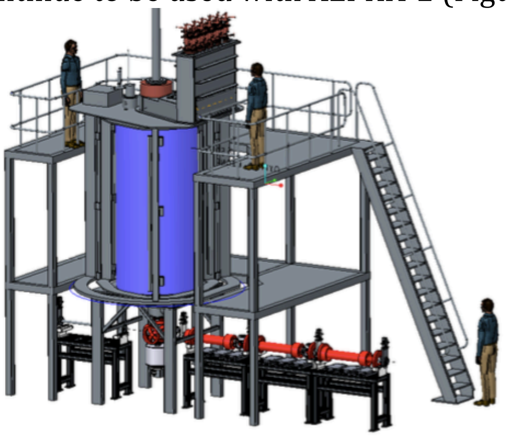


Figure 2. An elevation view of ALPHA-g above an interconnecting beamline. The new beamline modules (red) are shown schematically.

The ALPHA-g cryostat (Figure 3) is designed to operate the ten independent magnet circuits used to operate two superconducting Ioffe-type magnetic minimum traps, and the high-precision analysis normal-conducting magnets. Magnet connections will be made via high-temperature superconducting (HTS) leads operated in a manner similar to those in the LHC and ALPHA-2. Two independent Penning-Malmberg traps are operated in the top and bottom regions of the trap in order to manipulate antiproton and positron plasmas in order to produce antihydrogen. The cold volume is used to cool both the superconducting trap magnets and the internal vacuum structures in order to achieve the extreme high vacuum conditions necessary for long antimatter lifetimes. A top diagnostic station houses an electron source as well as diagnostics for extracted particles. The external TPC images antiproton annihilations over the length of the atom-trapping region. The external solenoid provides a uniform field over ~ 2 meter of plasma and atom traps while minimizing external stray fields on the existing ALPHA-2 infrastructure.

The cryostat design builds directly on the ALPHA-2 design, and we can directly duplicate the control systems for the current leads, liquid and gas flow systems, as well as the complete magnet power supply and quench protection systems. Likewise, control and sequencing systems for the Penning traps, plasma diagnostic and manipulation systems, and external detector systems (scintillators) are just being duplicated from ALPHA-2. Our philosophy, however, is to be able to operate both experiments independently – there will be no sharing of critical components. This will be crucially important when ELENA comes online and 24-hour operation with pbars is possible. Both the ALPHA-2 and ALPHA-g solenoids can be ramped up or down in a matter of minutes, if we need to minimize perturbations from one experiment on the other.

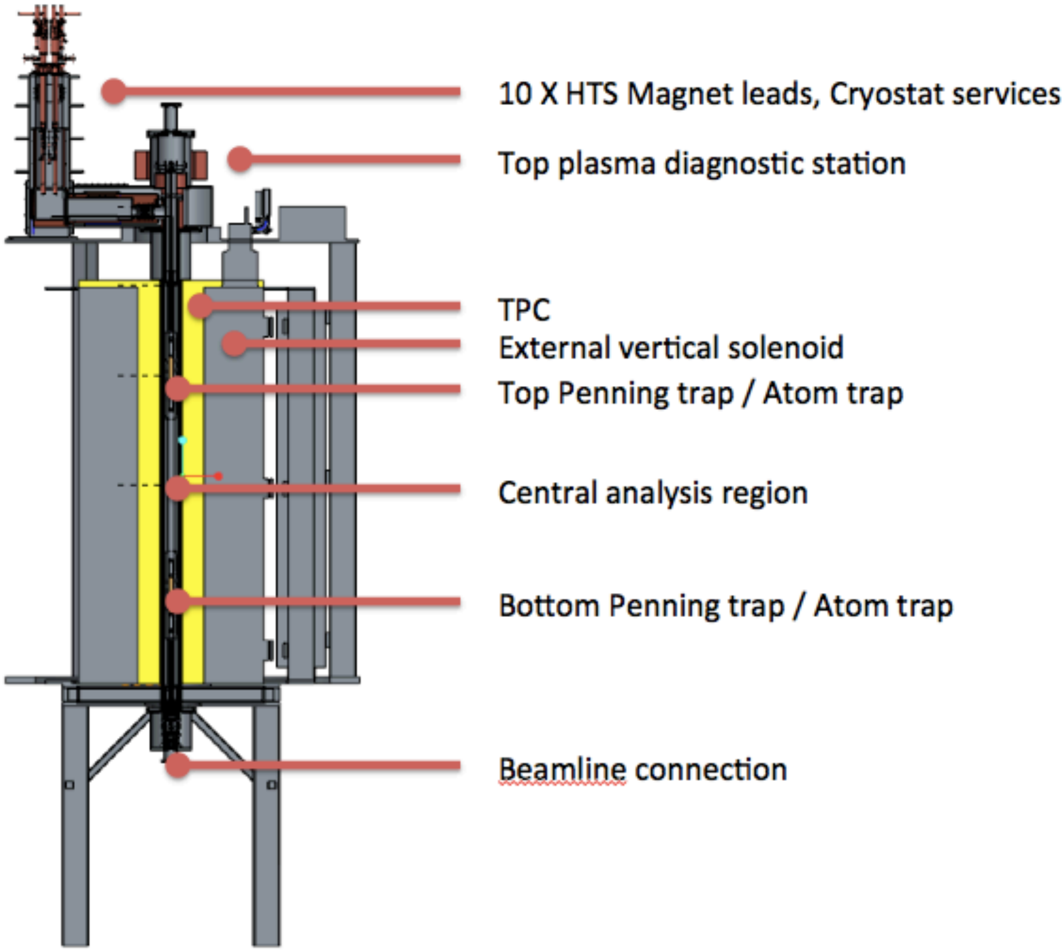


Figure 3. Cross section through ALPHA-g.
Cryostat components are marked with red pointers. The TPC volume is shown in yellow, with the outer vertical solenoid volume in gray.

Details of the measurement program

As is well known, gravity is a very weak force. The potential energy gained by an antihydrogen atom traversing one vertical meter is 1.6×10^{-26} J, or, in more convenient temperature units, about 1.2mK. ALPHA traps antihydrogen atoms with a truncated Maxwellian energy distribution maximized at about 500mK. Only about one antiatom in 10^{-4} has energy at or below 1.2mK, so it would seem that relatively few antiatoms would be significantly influenced by gravity in a reasonable sized trap. However, this difficulty can be overcome by making a differential measurement.

ALPHA contains antiatoms by confining them in a minimum-B trap. Antiatoms with antiparallel spins will be repelled by an increasing magnetic field; the energy gained by antiatoms as they move into such a field is approximately 670mK/T. Thus, a vertically aligned magnetic field will balance a gravitational field if it possesses a vertical gradient of about -18G/m.

ALPHA-g intends to trap antihydrogen atoms in a trap similar to the ALPHA and ALPHA-2 traps that have trapped over one thousand antiatoms. These traps use a magnetic octupole coil to provide radial confinement, and magnetic mirror coils to provide axial confinement. Unlike the previous two ALPHA traps, ALPHA-g will orient its axial direction vertically.

A simplified version of the ALPHA-g trap is shown below. The gold Penning trap electrodes are used to synthesize the antiatoms from trapped plasmas of antiprotons and positrons. The anti-atoms are then initially confined longitudinally between the topmost and bottommost red mirror coils, and transversely by the octupole. Ignoring the transverse motions, the antiatoms bounce between these two 1 T mirrors with a period on the order of 5 ms. ALPHA has confined antiatoms for times as long as 1000 s; the lifetimes are thought to be limited by annihilation on the background gas in the trap, a time likely to be ten or more hours.

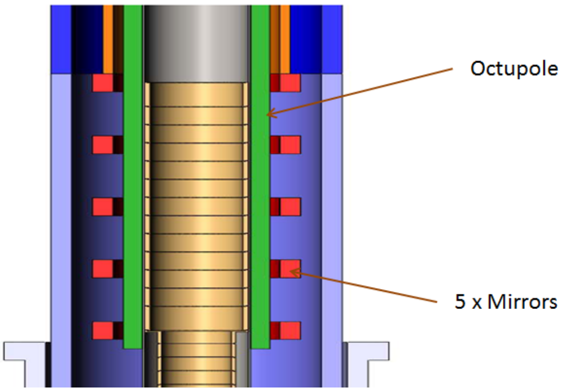


Figure 4. The ALPHA-g Penning and atom traps. The trap electrodes have an ID of about 44 mm.

With equal current in the two mirrors, the trap is magnetically symmetric along its vertical axis and the magnetic well barriers will be identical up and down. However, gravity will break this symmetry and make the well barrier slightly weaker at the bottom than at the top.

ALPHA-g will measure *g-bar* by slowly turning off the mirror currents, thereby allowing the anti-atoms to escape. Since we intend to use turnoff times on the order of 10s, the antiatoms will make roughly 1000 bounces during the magnetic turnoff interval. This allows the antiatoms to adiabatically sample the top and bottom well barriers. In one bounce, the field will have been reduced by a $\Delta B \approx (1\text{T})(5\text{ms}/10\text{s}) = 5\text{G}$. If the gravitational potential difference is greater than 670(K/T)×5G=340mK, or equivalently about 280mm, then the antiatom will fall out of the "proper" end of the trap, i.e. out of the bottom if the equivalence principle holds.

The actual antiatoms orbits are near chaotic, and the above scaling argument is simplistic. However, extensive computer simulations of the antiatom dynamics in the time-dependent magnetic fields demonstrate the validity of the calculation. Similar simulations have been used extensively by ALPHA in the past, and have been well validated against criteria like the experimental annihilation location and time of trapped antiatoms released from the ALPHA traps.

Note that in recent years, ALPHA has detected approximately one trapped anti-atom per trial; each trial takes about five minutes of real time. Using multivariable analysis (MVA) of the ALPHA-2 silicon detector annihilation data, the cosmic rate (cosmics misidentified as pbar annihilations) for a 10s period is about 0.05/trial, though we expect to do better than this with the new ALPHA-g TPC detector. Cosmics constitute the only detector-related errors we need to consider in these experiments.

We will consider two experiments: an Up/Down measurement that yields the sign of gravity for antiatoms, and a precision measurement that yields a measurement of *g-bar* to 1%.

Up/Down Measurement

The up/down measurement will be done in a trap very similar to the previous ALPHA traps. The mirrors in these traps are separated by about 280mm. Simulations show that, assuming normal g, 71% of the antiatoms escape downwards.
Consider the null hypothesis that antiatoms fall down. The table below summarizes the number of trials necessary to achieve the stated p-values under two conditions: 1- Antiatoms do not fall either up or down under gravity (upper entry in table); 2- Antiatoms fall upwards under gravity. We are most worried about a false positive result: we conclude that the hypothesis that antiatoms fall down if false.
From the table, we conclude that it takes approximately 400 trials, or about twenty hours of operation, to obtain three-sigma confidence in the null hypothesis that antiatoms fall down.

# Trials	0.0 Cosmics /Trial	0.1 Cosmics /Trial	0.2 Cosmics /Trial	0.5 Cosmics/Trial
20	0.748	0.845		
	0.033	0.362		
40	0.633	0.619	0.714	
	0	0.13	0.254	
65	0.461	0.545	0.614	0.742
	0	0.028	0.071	0.254
100	0.291	0.396	0.485	0.612
	0	0	0.017	0.217
200	0.05	0.138	0.2	0.412
	0	0	0	0.008
400	0.001	0.01	0.029	0.138
	0	0	0	0
650	0	0	0.002	0.038
	0	0	0	0
1000	0	0	0	0.004
	0	0	0	0
Zero entries are less than 0.001. Expected cosmic rate is 0.05/trial.				

The above table analyses statistical errors only. Systematic errors could be caused by magnet field imperfections. Such errors have been extensively studied.
We consider two types of errors:

Relative errors: Errors which are a constant fraction of the mirror coil field strength. These errors most likely result from asymmetries in the mirror coils themselves; e.g, the mirror coils could have different radii.

Absolute errors: Errors which are independent of the coil field strength. These errors most likely result from external and/or persistence fields that come from other magnets, most importantly, the ends of our octupole magnet.

These errors can cause the up/down fraction, 71% in the ideal system to diminish. Typical simulation study results are shown below:

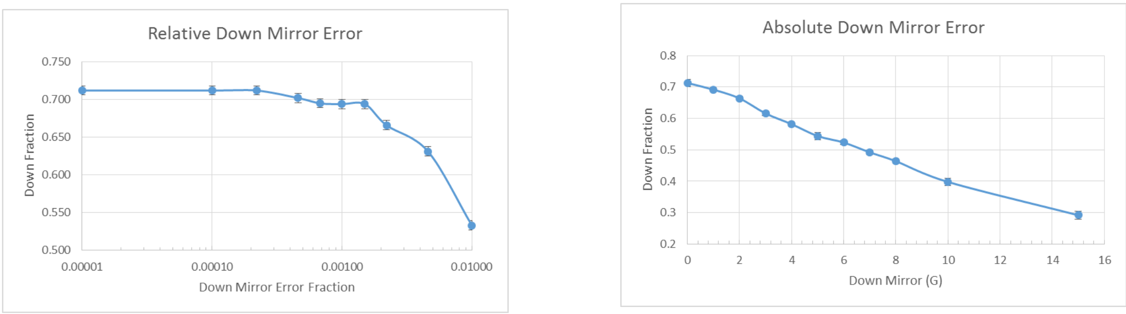


Figure 5. The effect of relative and absolute field errors on the observed down fraction (71% is ideal).

We can then ask what is the minimum down fraction we can tolerate and still reach a statistically significant result. If, for instance, we assume a maximum of 1000 trials, we can reach a false positive rate of p=0.01 when the down fraction is greater than 0.55.

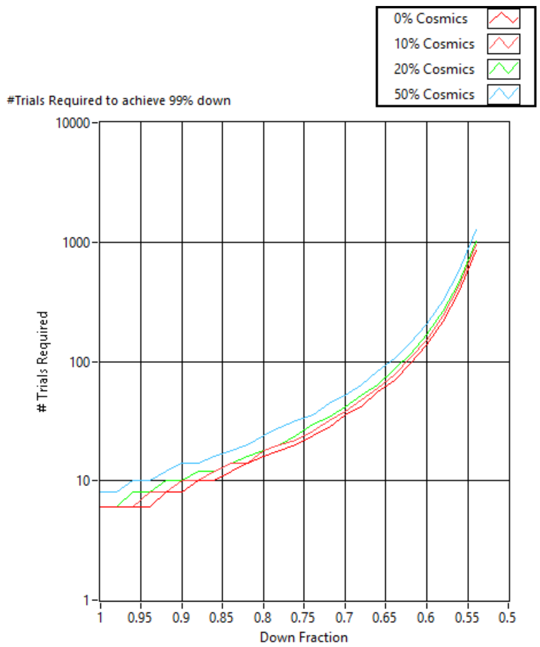


Figure 6. The number of trials required to achieve p=0.01 versus the calculated down fraction for various levels of cosmic contamination.

From the earlier graphs, we conclude that we can tolerate a relative mirror error of nearly 1%, and an absolute error of 5 *G*. Other studies show that the relative error criterion is readily achievable. Given that the octupole and external solenoid in our experiments have fields on the order of 1T, achieving the absolute error criterion requires precise magnet design and construction, and the magnets have been designed accordingly.

Precision Measurement

Because of the sensitivity of a precision measurement to magnetic field errors, we will move the antiatoms to a special, "analysis" region of our apparatus where the external fields are lower and more uniform. To reduce persistent field effects in superconductors, the axial magnetic well in this region will be created by special copper "analysis" coils. We will move the atoms with an adiabatic transfer procedure that involves the manipulation of the five mirror and two analysis coils in our system.

An example field manipulation procedure is shown in the video below.

5mirror.mp4

Because the copper analysis coils are limited to about 1kG, only about 17% of the antiatoms are retained in the expansion procedure. This is a significant loss, but is ameliorated by the fact that the antiatoms will be significantly cooled: to at least below 50mK. Thus the retained antiatoms are much more sensitive to gravity. For example, if we were to do an up/down measurement in the analysis region with the cooled sample, 100% (assuming normal gravity) would escape down. Indeed, with a simple release experiment, i.e., slowly turning off the analysis coils, we get no precision information because the experiment is only sensitive to the sign of *g-bar*, not to its magnitude.

To make a precision measurement, we intend to employ a magnetic gradient coil that balances gravity. Assuming normal gravity, a gradient of +18 *G/m* will precisely cancel gravity, and equal numbers (within statistics) of antiatoms will fall out of the trap in the upward and downward direction. This process has been extensively simulated. Typical results are shown in the graph below, which plots the up-down average as a function of the gradient field; the curve of this average as a function of *g* is identical if the gradient is set to +18 G/m.

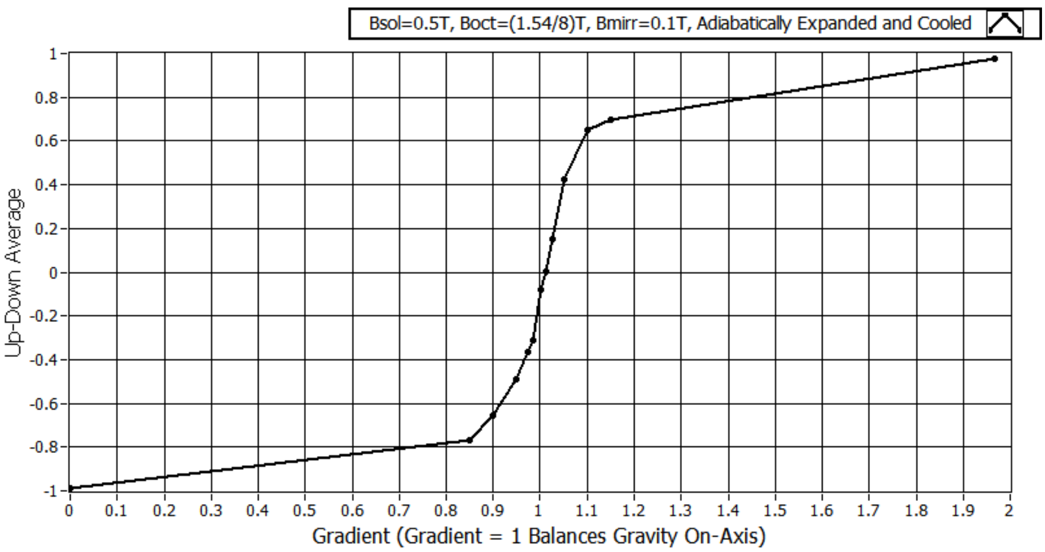


Figure 7. The Up – Down average, i.e., $(N_{up}-N_{down})/(N_{up}+N_{down})$, versus the strength of the applied magnetic field gradient.

Because this curve is quite sharp, we can make an accurate measurement of g. The procedure would be to set the gradient coil to +18G/m, measure the up-down average or some equivalent metric, and use this curve to infer *g-bar*. For instance, if we were to measure an up-down average of -0.6, we would have determined that $g \approx (1/0.92)g_0$. The error in this measurement would be related to the number of trials, as shown in the table below.

Approximate Number of Trials	Number of Antiatoms Analysed	1σ percent error on g No cosmics	1σ percent error on g 10% cosmics	1σ per cent error on g 75% cosmics
58	10	3	4	100
175	30	1.7	2.5	18
585	100	0.9	1.2	3.3
1754	300	0.5	0.7	3.3
5848	1000	0.3	0.4	1.6

These results assume no systematic errors. There are two sources of systematic errors. The first comes from reliance on simulations to determine the shape of the discrimination curve. This error, which comes from inexact magnet field models, and assumptions about the energy distribution of the trapped antiatoms, currently suggests a 1% effect on the determination of *g-bar*. The other source of error comes from magnetic field errors. To make a 1% measurement, we need to control these errors to the 0.1 G level.

Magnet Construction

The successful execution of the above measurements requires a very careful magnet design. To ensure the magnetic symmetry of our system, we intend to build an up/down symmetric system. At the very top and bottom of our trap will be two regions capable of recapturing positrons and antiprotons from our positron accumulator and from our antiproton catching trap. In slightly from both ends will be two regions independently capable of synthesizing and trapping antihydrogen, and of making an up/down measurement. The analysis region will be in the center of the trap. An early schematic of the trap is shown below (rotated horizontally for ease of display).

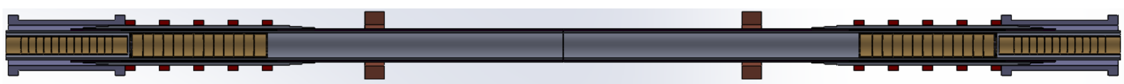
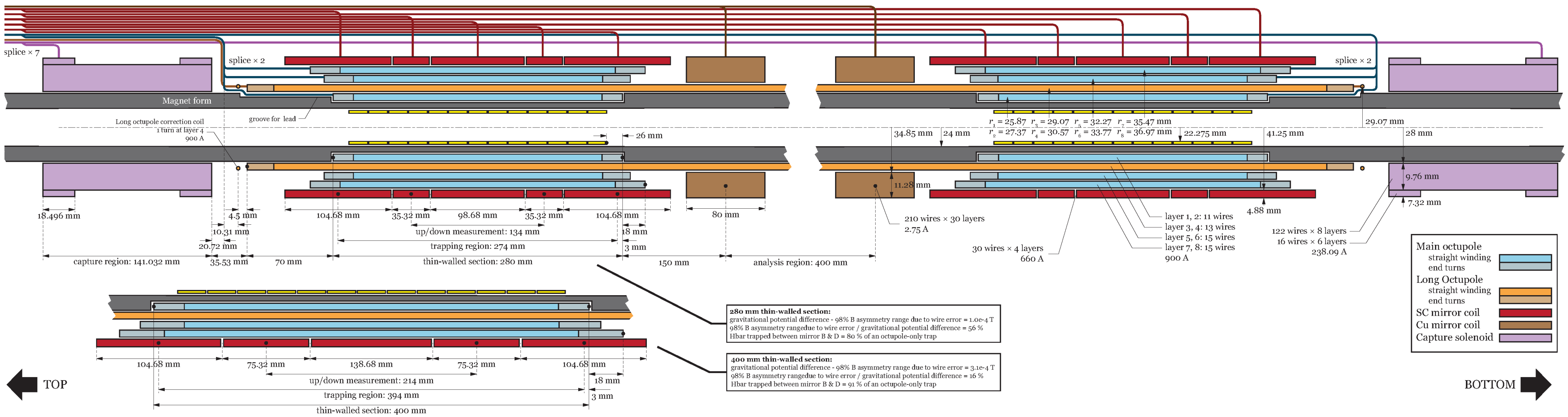


Figure 8. Schematic of the internal portion of the ALPHA-g device, rotated to the horizontal plane. A complete antihydrogen synthesis and trapping region (Penning trap and atom trap) occupies each end (top and bottom) of the machine. The central analysis region confines antiatoms using copper mirror coils and a reduced-strength octupole.

We have performed extensive design studies for the magnet system for this trap. The design is still evolving, but we now have a design that, in the absence of magnet construction errors, meets all of our design criterion. A summary of this design is shown on the next page. We do not discuss the details here.



splice × 7
splice × 2
splice × 2
Magnet form
groove for lead
Long octupole correction coil
1 turn at layer 4
900 A
26 mm
18.496 mm
4.5 mm
10.31 mm
20.72 mm
35.53 mm
capture region: 141.032 mm
70 mm
104.68 mm
35.32 mm
98.68 mm
35.32 mm
104.68 mm
up/down measurement: 134 mm
trapping region: 274 mm
thin-walled section: 280 mm
18 mm
3 mm
80 mm
150 mm
analysis region: 400 mm
34.85 mm
24 mm
11.28 mm
210 wires × 30 layers
2.75 A
30 wires × 4 layers
660 A
r_1 = 25.87 r_3 = 29.07 r_5 = 32.27 r_7 = 35.47 mm
r_2 = 27.37 r_4 = 30.57 r_6 = 33.77 r_8 = 36.97 mm
22.275 mm
41.25 mm
4.88 mm
layer 1, 2: 11 wires
layer 3, 4: 13 wires
layer 5, 6: 15 wires
layer 7, 8: 15 wires
900 A
29.07 mm
28 mm
9.76 mm
7.32 mm
122 wires × 8 layers
16 wires × 6 layers
238.09 A
Main octupole
straight winding
end turns
Long Octupole
straight winding
end turns
SC mirror coil
Cu mirror coil
Capture solenoid
104.68 mm
75.32 mm
138.68 mm
75.32 mm
104.68 mm
up/down measurement: 214 mm
trapping region: 394 mm
thin-walled section: 400 mm
18 mm
3 mm
280 mm thin-walled section:
gravitational potential difference - 98% B asymmetry range due to wire error = 1.0e-4 T
98% B asymmetry rangedue to wire error / gravitational potential difference = 56 %
Hbar trapped between mirror B & D = 80 % of an octupole-only trap
400 mm thin-walled section:
gravitational potential difference - 98% B asymmetry range due to wire error = 3.1e-4 T
98% B asymmetry rangedue to wire error / gravitational potential difference = 16 %
Hbar trapped between mirror B & D = 91 % of an octupole-only trap
TOP
BOTTOM

The magnet system will be constructed by the Brookhaven National Laboratory (BNL) using their direct wind machine. This machine ultrasonically glues wires in place before applying fiberglass and epoxy to contain the magnetic forces. BNL quotes a wire placement accuracy of 0.001 inch (0.025mm). This is the same technology that has been used successfully for the ALPHA and ALPHA-2 magnets.

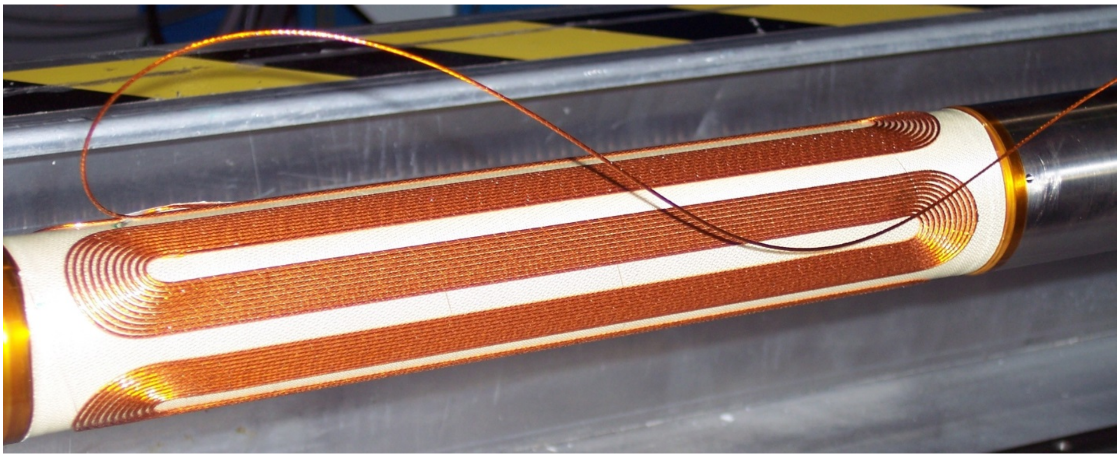


Figure 9. An ALPHA octupole magnet being wound at BNL. The superconductor is 1mm in diameter. The finished octupole comprises eight such layers. The beam tube diameter is about 50 mm.

We are currently concluding a study of the sensitivity of our design to magnetic construction errors. The most significant source of errors in the design comes from misplaced wires in the octupole. For example, one error that we have studied comes from wire displacement as shown in the image below, where the arrows indicate the direction of the displacement of the wires from their true position (shown as the dotted lines):

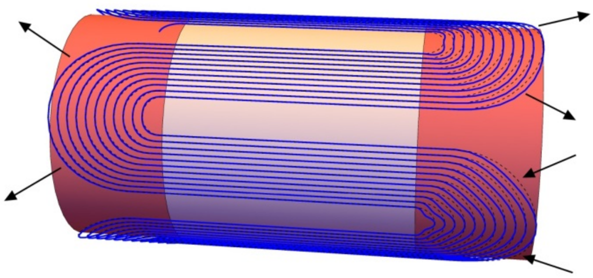


Figure 10. An illustration of some of the magnet winding errors being considered for ALPHA-g. We simulate the effects of wires (solid blue lines) that are displaced from their design positions (dotted blue lines). Note that we also carefully model the positions of the leads to each coil.

Because of layer-to-layer cancellation, the effect of these errors is unimportant if the error is same in each layer. More important are errors in which each layer is different. The effect of this error is shown below. Each curve represents the field with a particular instance of random wire deviations selected from a distribution with a standard deviation of 0.002 inch: twice the quoted BNL error. These deviations limit how long the up/down and analysis regions can be for a fixed octupole length. We have used these simulated results in optimising the current design, and we are working closely with BNL to minimise positioning errors and their impact.

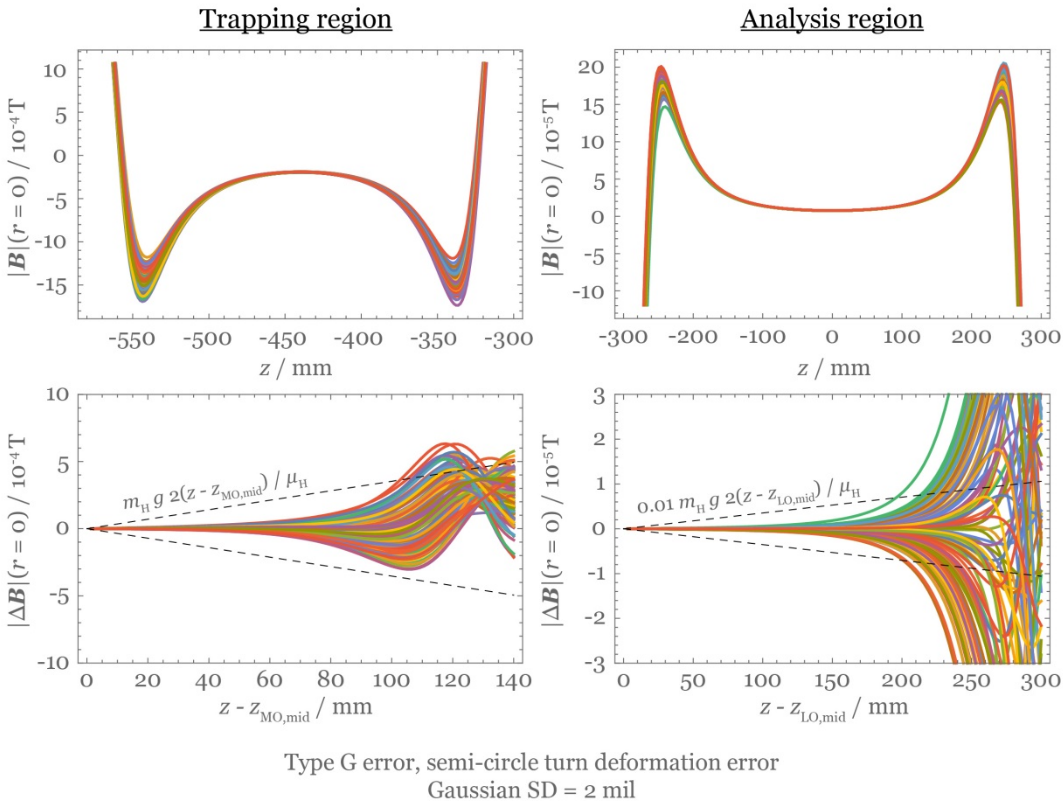


Figure 11. Magnetic field errors in the trapping regions (left) and in the analysis region (right) caused by wire displacements. Each coloured curve represents a configuration of wire positioning errors chosen from a distribution having a standard deviation of about 50 microns.

Magnetometry

We have undertaken a significant design effort to build suitable *in-situ* magnetic probes to aid with the precision measurement of *g-bar.* Determining the as-built field errors will allow us to improve the accuracy of a measurement of *g-bar* in the longer term. This is work in progress by our Canadian colleagues, who are experts in magnetic measurement for NMR applications, and is relevant for the second phase of ALPHA-g. We will keep the SPSC informed on progress on this project at our yearly reviews. We are optimistic about improving the accuracy on *g-bar* beyond the 1% level, but this work is preliminary. Provisions for *in-situ* magnetometry are included in the cryostat design, so we anticipate no major intervention into the internal apparatus to retrofit this capability.

Annihilation vertex detector

1.Requirements

The ALPHA-g apparatus will measure the gravitational interaction of trapped antihydrogen via detecting the annihilations of antihydrogen atoms (see the physics section). The trajectories the annihilation product (mostly charged pions) are reconstructed to determine the time and the position of the annihilation vertex. The primary requirements for the detection system include: (a) large area coverage, (b) high reconstruction efficiency, (c) vertex resolution of order several mm, (d) high cosmic background rejection efficiency. Specifically:

(a) Dimension:

Vertical dimension: an active length of 2.3 m. This is much larger than the ALPHA-2 axial Si coverage of 46 cm. Radial space available: Inner radius: 10 cm; Outer radius: less than 25 cm. These are limited by the size of the cryostat, and the external solenoid magnet, respectively. The scintillator barrel also has to fit into this volume (see below).

(b) Reconstruction efficiency:

Because of the expected low event rate of the experiment, reconstruction efficiency of better than 90% is desired, throughout the trapping volume of ~ 2 m in length (we cannot have a significant dead volume). Efficient track pattern recognition is a key to attaining a high reconstruction efficiency.

(c) Vertex resolution:

Because of the large amount of scattering materials (such as superconducting magnets and the cryostat) between the annihilation point and the tracking detector, the position resolution for the annihilation vertex is limited to several *mm*, even with an ideal hit resolution in the tracker. For example, for the ALPHA-2 Si detector, our estimated resolution was ~5 mm (sigma) for the *z*-, ~9 mm for the *r*-, and ~18 degrees for the phi-coordinate. For the diagnostics of trapped antihydrogen dynamics, a vertex resolution similar to the ALPHA-2 tracker is desired. However, for the gravity measurements, the requirement for the position resolution is much less stringent and several *cm* would be sufficient.

(d) Cosmic background rejection

One of the key design criteria for the ALPHA-g detector is the ability for cosmic rejection. Our goal is to reduce the cosmic rate (cosmic rays misidentified as antiproton annihilations) by a factor of 10 compared to the ALPHA-2 case, to the level of $5 \times 10^{-4}\ s^{-1}$, in order to maximize our ultimate physics potential for gravity measurements.

(e) Event rates

The event rates during the main "gravity physics" measurements are dominated by cosmic background, as our physics rates can be as low as one event per many minutes. The expected rate for the cosmics is currently being simulated, but will probably be of order of 100 Hz. If the rate is too high, we would cut down the rate at the trigger level.

2. Tracker Design Concept

We have successfully constructed and operated 3-layer double-sided silicon vertex detectors for the ALPHA and ALPHA-2 machines. However, given the requirement for the large area coverage, Si is not practical because of the cost and the time required for the production. Therefore, we have adopted a time projection chamber as our primary tracker. Alternative solutions have been considered such as:

- Cylindrical GEMs or Micromegas providing at least 3 intersection points (similar to the silicon detector but on a larger scale). The ASACUSA experiment uses a tracker based on 2 layers of double-sided Micromegas tracker. The detector is used for monitoring of antihydrogen production with high rates. This type of the detector will have a limited track recognition capability, since the cells are connected in one direction on the front-side, and in the other direct in the back side. Also, this detector cannot be made very large without having a significant dead region. Furthermore, covering a large area would be quite expensive.
- The standard (axial drift) TPC concept is an attractive proposition as this type of detector is well established. In this particular case, the geometry is odd as the drift distance is ~2 m in a restrained radial space of 7 cm. The main reasons for rejecting this option are: 1) we wish to retain the possibility of operating the TPC with a low or no axial magnetic field, 2) the non-uniform fringe magnetic fields from the magnetic trap may disrupt the long axial drift of the electrons (by sending them to the walls). Furthermore electron drifting in this volume would be affected by, inhomogeneity of the field cage, and large transversal and longitudinal diffusion for such a restricted signal collection region.
- A radial-drift TPC has been adopted as our solution. In this configuration, the magnetic field (vertical) is perpendicular to the radial electric field generating a Lorentz force on the electrons traveling towards the anode. This results in a spread of charge over several wires from a single particle track crossing the drift volume. Electron multiplication is produced with standard wires stretched between the two ends of the cylinder. The *phi*- and *z*- coordinates for the position of ionization are determined by the signal in the anode wires and cathode pads, and the *r*-coordinate by the electron drift time.

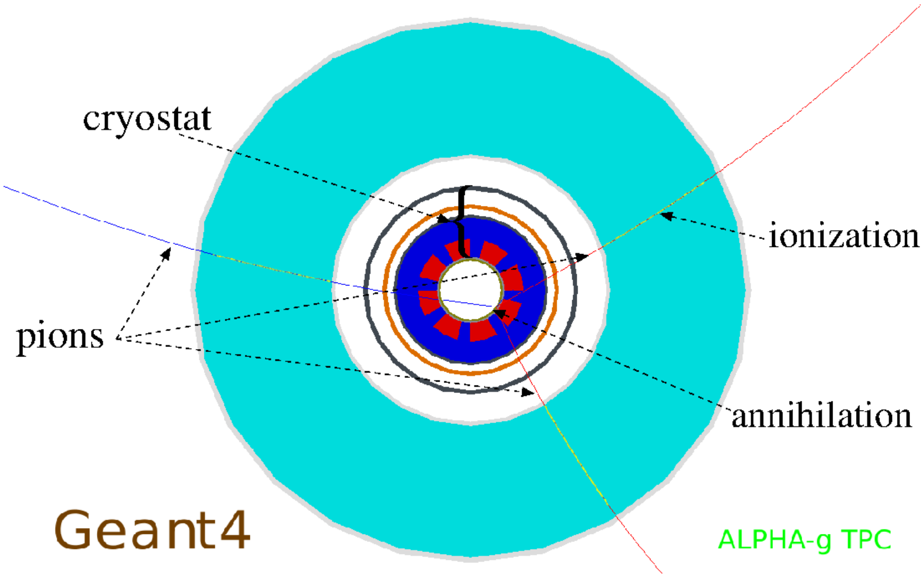


Figure 12. Cross-sectional view of the ALPHA-g apparatus with the radial drift TPC

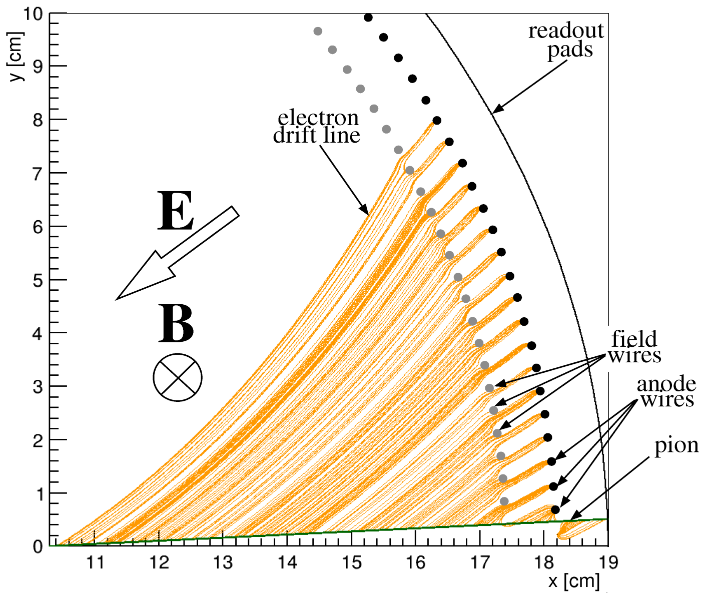


Figure 13. Garfield^{++} simulation for a radial-drift TPC. A pion track (green) emitted in the x-direction (φ = 0) and bent by a 1 T magnetic field. Orange lines are electron drift lines. A gas mixture of 90-10 Ar-CO_2 is assumed.

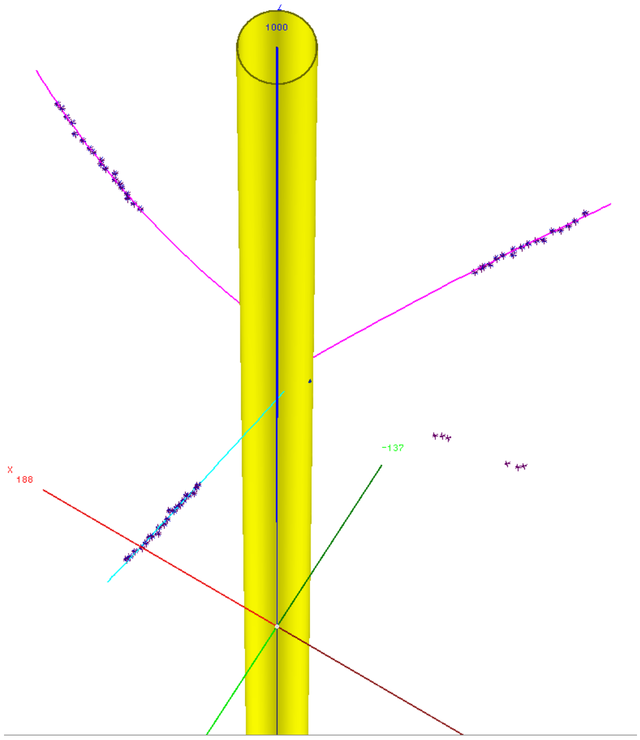


Figure 14. GEANT4 simulation of an antiproton annihilation into three charged pions (magenta and cyan), and the corresponding reconstructed helices from the spacepoints of ionization in the TPC (blue). The antihydrogen trapping region is shown in yellow.

TPC calibration:
While our required hit resolution is lenient compared to state-of-art TPCs, we will implement a laser calibration system, based on the T2K TPC system.

Readout and data acquisition:
There will be 256 anode wires with a 4.5 mm pitch and 18,432 cathode pads (4 mm x 32 mm each). The signals from the anode wires will be digitized on both ends with digitizers having 65 to 100 MHz sampling rate. The relative amplitudes of the wire signals at both ends will provide some z position information. The cathode pads signals will be read out via the AFTER chips, a custom ASIC from Saclay, originally developed for the T2K Near Detector TPC. The data acquisition system will be based on the MIDAS system, developed at PSI and TRIUMF, and successfully adopted to the ALPHA and ALPHA-2 experiments. The TPC readout will be triggered either by the external scintillator barrel (see below), or by self-triggering on the anode wire signal. A readout rate of few hundred Hz is expected, which is sufficient for gravity physics with antimatter.

3. Cosmic Rejection

In the ALPHA and ALPHA-2 experiments, cosmic rejection relied on the event topology In ALPHA-g, we will use event topology (a) and we will implement a time-of-flight based cosmic rejection scheme (b).

(a) Topology based cosmic rejection

In this scheme, we discriminate the cosmic from the antihydrogen annihilations based on the event topologies. In the ALPHA Si detector, for which we had only 3 layers of (double sided) Si strip modules, the topological discrimination power was limited. With the proposed TPC, the track pattern recognition and the topological rejection of the cosmics are expected to improve dramatically, since the amount of information obtained for each event is much greater. Roughly speaking, the TPC is equivalent to having >20 points of measurement for each track, compared to 3 in Si, and the TPC has much less of the hit ambiguity (ghosting) inherent in double-sided Si.

(b) Time-of-flight cosmic rejection and TPC Trigger

For the purpose of triggering the TPC readout, and to reject the cosmic background via time-of-flight, a barrel of scintillator bars read out by SiPM will be used. The necessary time resolution is of order of few 100 ps (sigma).

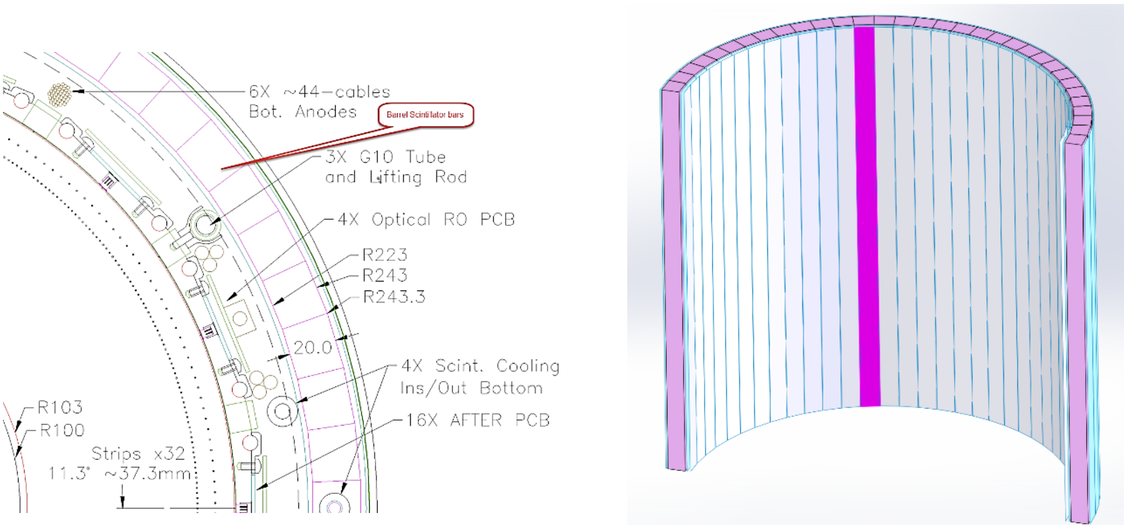


Figure 15. Partial cross section of the detector volume, showing the position of the barrel scintillator.

4. Design Details

The development and the construction of the ALPHA-g detector is led by the TRIUMF Detector Group, which has a long history of constructing gas detectors, including the Babar drift chamber and the T2K TPC. Details for the TPC simulations (Garfield++ and GEANT4), mechanical design, readout/DAQ scheme etc., can be found in TRIUMF design notes, available upon request. Some examples of the design work are given below.

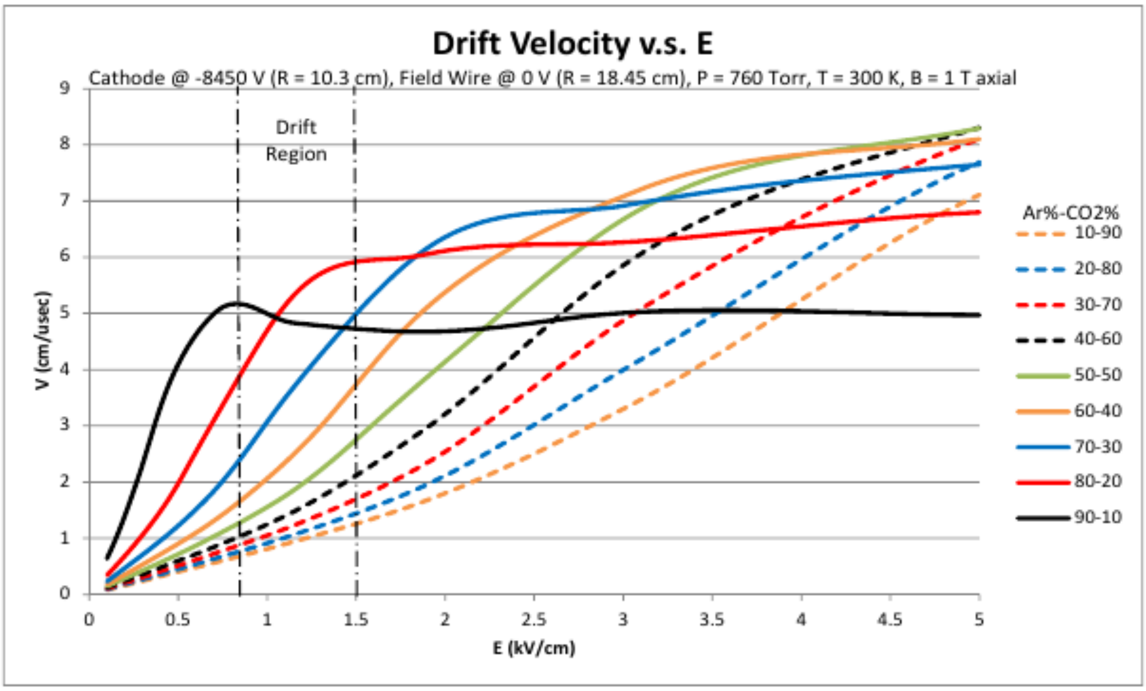


Figure 16. Electron drift velocity in different gas mixtures. We expect to use 90-10 Ar-CO_2 for ALPHA-g.

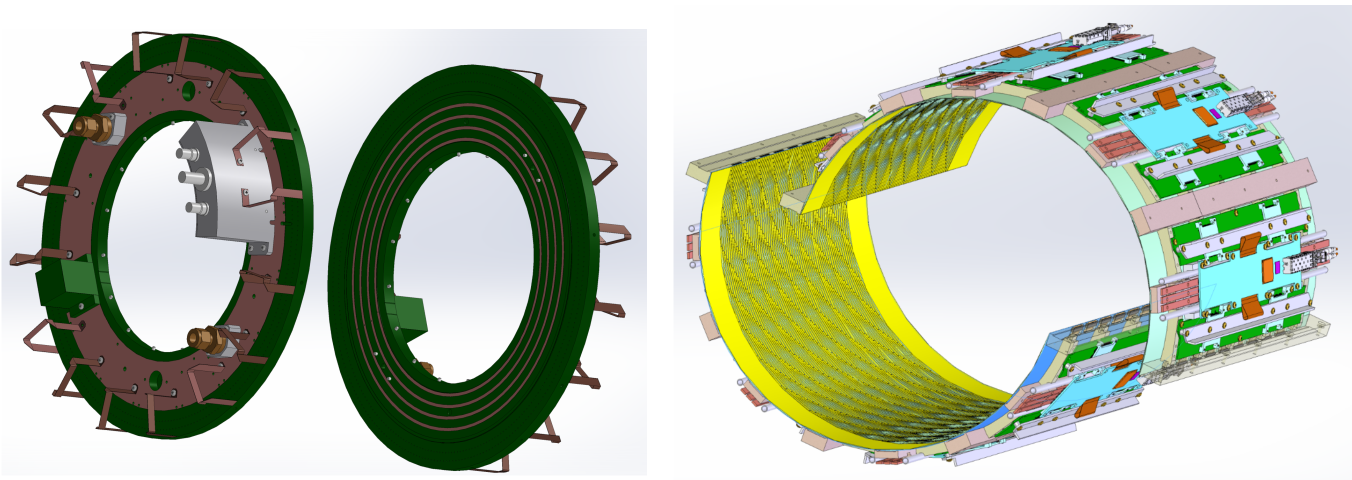


Figure 17. Design of the end plates and outer half-cylinders (1/8 of the total length is shown).

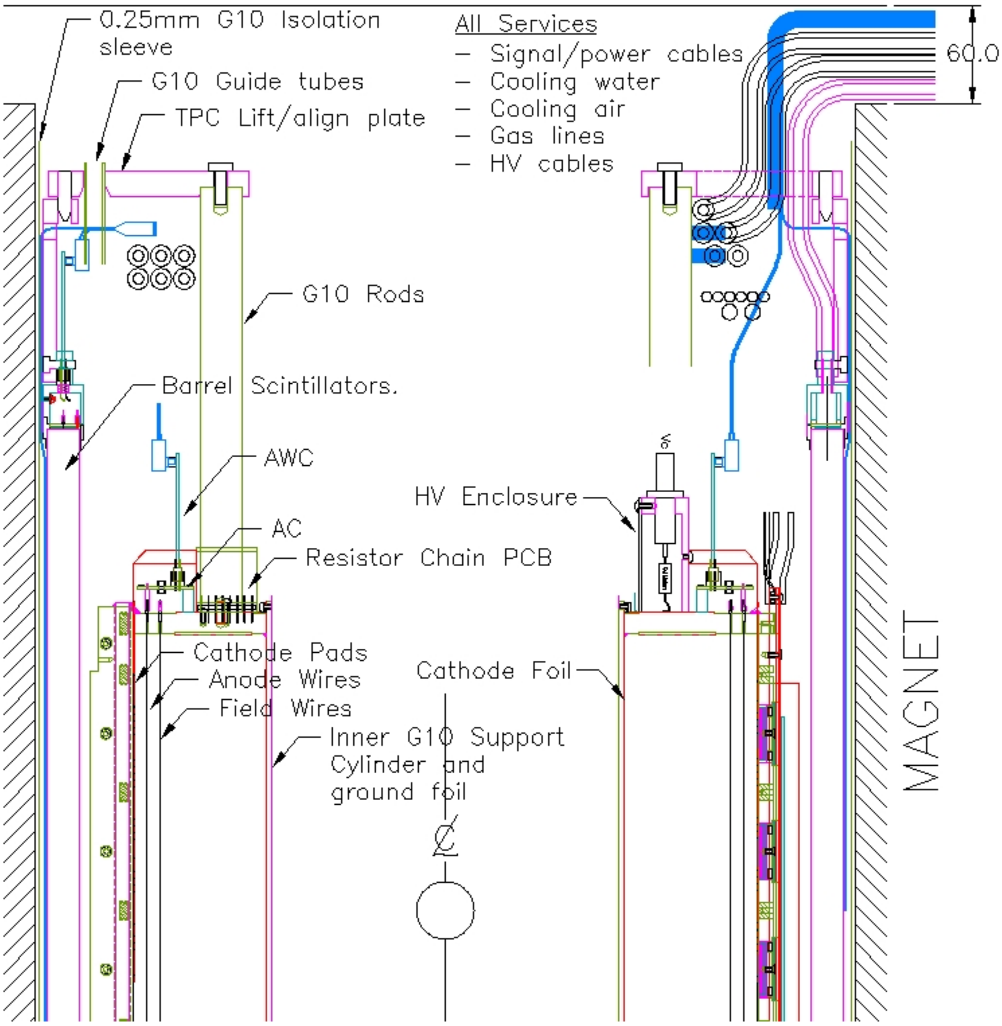


Figure 18. Configuration of the top end of the TPC and Barrel Scintillator. The anode cards (AC and AWC), and HV enclosure for *Vc, Va,* and *Vfw* are indicated. The services to the bottom end come up through 'gaps'. All services exit the external solenoid magnet though a 60mm tall gap (top-right) in a sector facing the nearby support platform.

Status

The detailed design of the TPC is complete and a prototype module has been is constructed and is currently being tested at TRIUMF. We expect the completed detector to arrive at CERN in September of 2017.

Executive summary – estimated schedule and impact on ALPHA-2

The design of the major new components necessary for ALPHA-g is essentially complete, and we are starting fabrication and procurement of the long lead-time items. Our goal is to assemble the components on the floor of the AD in the autumn of 2017. Our current planning assumes that the installation of the ELENA beamlines will not take place in 2017, and that the 2017 running period will have a "normal" duration. In this scenario, we would hope to trap charged particles in ALPHA-g before the end of 2017. We feel that this schedule is realistic, given our recent experience with ALPHA-2. One possible complication is with the fabrication of the external solenoid. We have allowed more than one year for this, and Oxford is capable of meeting this deadline if there are no complications in the fabrication. The magnet is of conventional superconducting construction and is not technically challenging. However, the size of the magnet requires some fabrication facilities to be adapted, and this could potentially lead to delays. The remaining portions of the new ALPHA-g apparatus - those that we control directly - are expected to be finished on time.

We are also assuming that no major modifications to the existing ALPHA-2 apparatus will be necessary in the end-of-year shutdown in 2016. We undertook an extensive redesign of the internal optical system of ALPHA-2 this year, and we are concentrating on the 1s-2s spectroscopy experiment during this run and will continue to do so for the bulk of the 2017 run.

The installation of ALPHA-g at CERN would take place well after the start-up of ALPHA-2 in 2017, and would take place in the 16 hours daily of pbar-off time. As is well known, we man our experiment 24 hours a day and are accustomed to this type of operation. The start-up of ALPHA-2 this year has not been impacted by ALPHA-g activities, and we are proceeding well on the 1s-2s setup. We expect the collaboration to grow by four to five postdocs in the coming year, so that the installation of ALPHA-g will be manageable in 2017. We have concentrated much of the ALPHA-g design work offsite, and the new Danish and Canadian funding supplies much more engineering support than we had for ALPHA-2. The cryostat/beamline design team from RAL will supply additional manpower for the labour-intensive installation phase of ALPHA-g, as will the detector group at TRIUMF.

There will be an obvious decision point in the summer of 2017 on whether to proceed with the installation of ALPHA-g or not in 2017. We currently see no reason to doubt that we can have finished components on site on time, but this decision will also obviously depend on the progress on the physics program with ALPHA-2. The schedule is designed to minimise the impact on the ALPHA-2 program, and we hope that we will succeed with the first laser spectroscopy before ALPHA-g arrives at CERN. The important step for 2016 is the expansion of the ALPHA zone in building 193 to allow space for ALPHA-g in 2017.

We hope that the SPSC will support our ambitious efforts to build a credible gravity experiment based on proven technology and techniques. We are confident that the ALPHA collaboration can execute this plan and be competitive in this emerging field in both the near and the long term. The scientific program has already been peer-reviewed for the Danish and Canadian funding applications, and we can of course provide much more technical detail if necessary. We kindly ask that you treat this addendum confidentially (within the committee) if possible.

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