Report to the CERN SPSC
Progress of the ALPHA Experiment in 2022

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The ALPHA experiment was first operated with the 100 keV ELENA beam in the short run in 2021. The 2022 beamtime was thus the first full year of physics operation since LS2. The priority of the collaboration was to begin physics with the new ALPHA-g experiment. This campaign was very successful. We did, however, dedicate a few weeks of beam to the ALPHA-2 apparatus.

1. Re-commissioning of ALPHA-2

As we have previously described, the external solenoid magnet for ALPHA-g was delivered from the manufacturer with a cryo-cooler system that is marginal for the intended operation of the magnet. Specifically, it requires the entire system to be warmed up to room temperature occasionally, resulting in a three-week downtime for ALPHA-g. During one such period in 2022, we devoted the available beam from ELENA to studies with ALPHA-2. The intent was to confirm that all of the hardware was functioning properly and to re-establish the capabilities for antihydrogen spectroscopy and laser cooling that we had previously demonstrated.

The pulsed Lyman-alpha laser that is used for laser cooling and spectroscopy of trapped antihydrogen was upgraded during LS-2. The new system has a higher pulse repetition rate (50 Hz instead of 10 Hz) and a new, more reproducible, gas control system for the third harmonic generation cell. In order to commission this system in 2022, we performed some initial studies of laser cooling of trapped antihydrogen for various fixed laser detunings. The original result[1] from 2018 was a proof-of-principle experiment with a single, fixed laser detuning that was determined from simulations. There was no time to optimize the laser cooling before the beam stopped for LS2.

For the current studies, antihydrogen atoms were accumulated for several hours, then the trapped atoms were exposed to the cooling laser at the $1S_d$ – $2P_a$ transition (Figure 1) for three hours. After the cooling, the trapped atoms were probed with the laser at the $1S_d$ – $2P_c$ transition to measure the Lyman-alpha linewidth and to obtain the annihilation time-of-flight spectrum that characterizes the transverse energy.

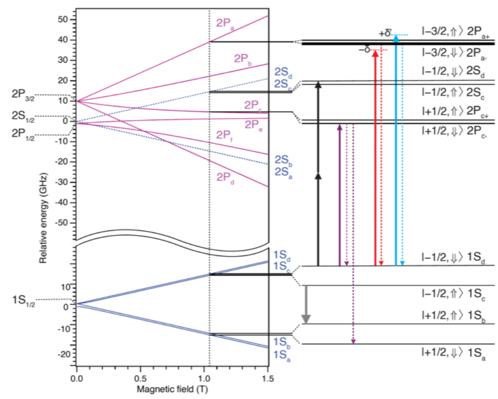

Figure 1. Energy levels for the 1s and 2p states of hydrogen in a magnetic field.

The measured line shapes for three different detunings are shown in Figure 1. Also shown are the line shape with no cooling immediately after accumulation, and the line shape with no cooling and after a three hour wait to match the cooling time. Roughly speaking, the dependence on detuning seems to be minimal so far, but all of the cooled lines appear to be slightly narrower than the original result published in *nature*. The time-of-flight data support this observation. (Fig3). This is presumably due to the increased cooling power, but we have not had the experimental time to do the necessary systematic studies to confirm this or to get these data into a publishable form. We thus hesitate to make quantitative conclusions at this point. Note that the integrated laser energy for these runs was up to a factor of 25 larger than in 2018. We will focus on ALPHA-2 again in 2023.

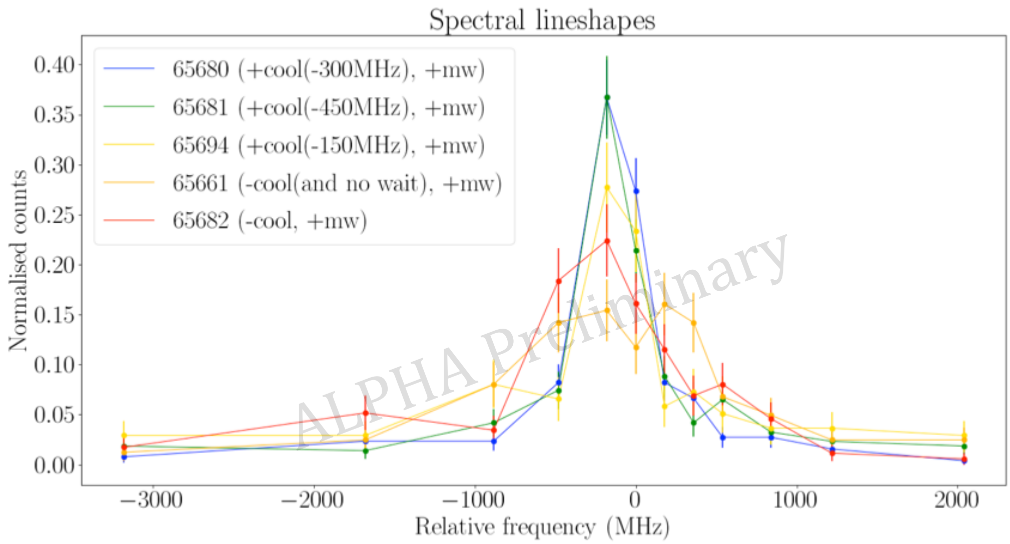

Figure 2. Lyman-alpha line-shapes measured after laser cooling at various detunings, or without cooling.

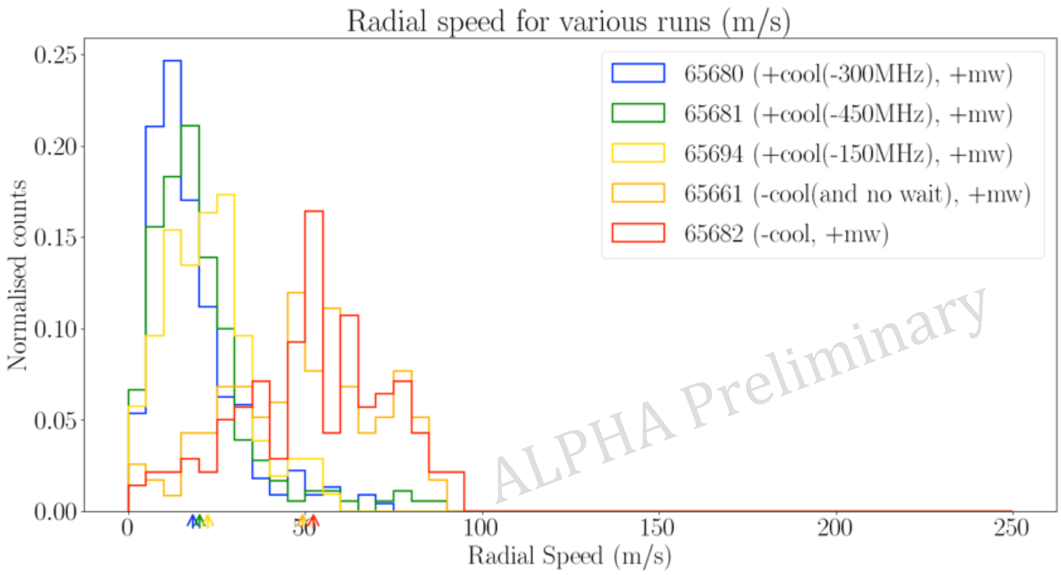

Figure 3. The radial speed distributions extracted from the time-of-flight data for the laser cooling runs.

We also managed a brief attempt at 1S-2S spectroscopy during the same running period. Figure 4 shows a spectrum for the d-d transition, measured *without* laser cooling. Time constraints again meant that we didn't get to measure this transition after laser cooling.

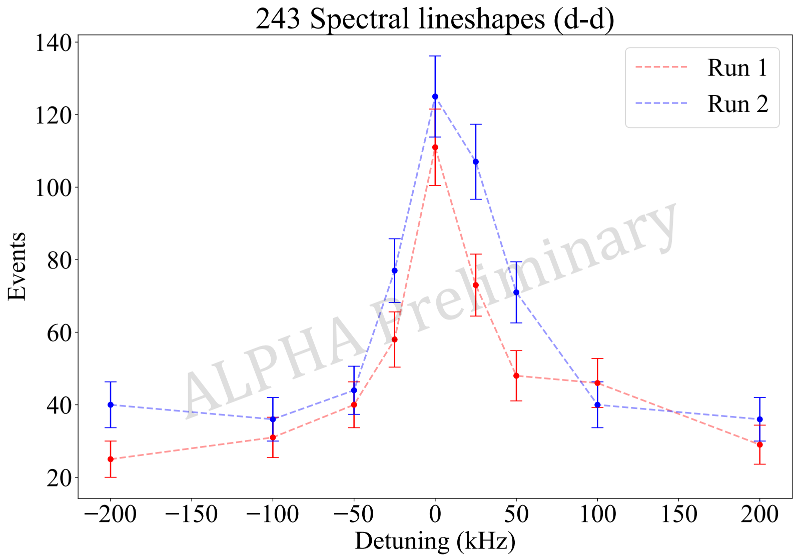

Figure 4. Two measurements of the 1s-2s transition without laser cooling. This is for the d-d component only.

Finally, the Cesium Fountain Clock (Fig. 5) was delivered to ALPHA from the National Physical Laboratory in September of 2022. The clock is now operational and is being characterized for use during the 2023 physics run.

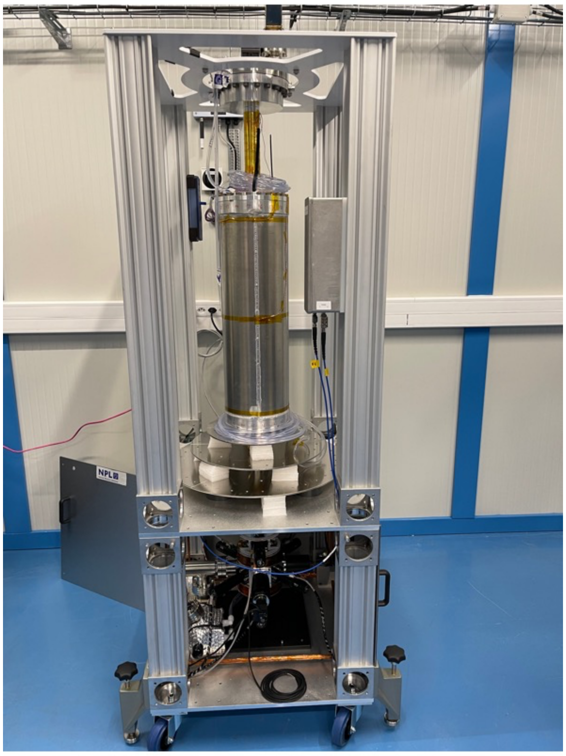

Figure 5. The 'physics package' of the cesium fountain clock purchased from NPL. The magnetic shielding and outer enclosure have been removed.

2. Work on gravitation in ALPHA-g

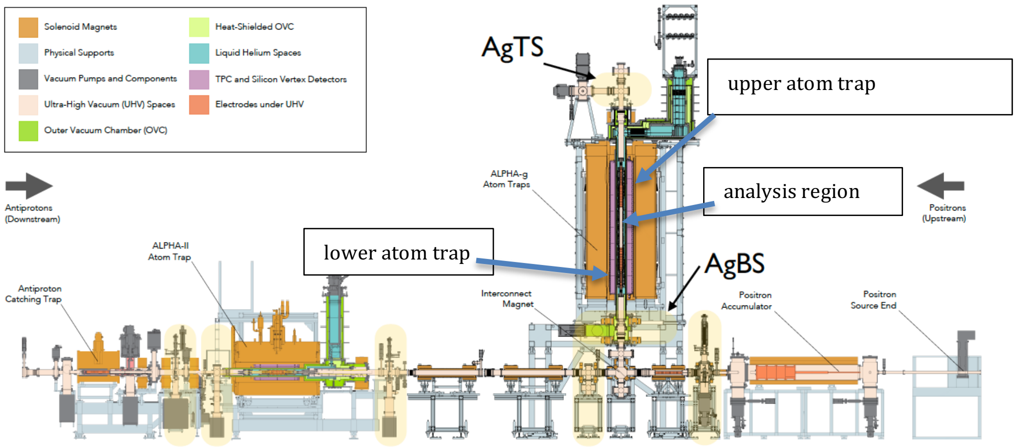

Figure 6. Schematic of the complete ALPHA apparatus.

Our main goal for the 2022 run was to finish the commissioning of the ALPHA-g machine (Fig6) and to begin studies of the gravitational behaviour of antimatter. In particular, the concrete plan was to perform the so-called 'up-down' measurement to determine the direction of the gravitational force from the Earth on antimatter. General Relativity predicts this force to be attractive and identical to that of matter, but there have been no direct measurements to verify this.

During the shortened run of 2021, we managed to commission the ALPHA-g Penning traps with electrons, positrons, and antiprotons, and to start systematic studies for producing antihydrogen. We did not attempt to trap antihydrogen in 2021. The magnet systems for the antihydrogen trap were not fully commissioned in 2021, and this has been a major focus since the end of the last run.

In brief, ALPHA-g is now fully operational. Antihydrogen atoms have been trapped and accumulated for several hours, although the peak trapping rate (5 atoms/mixing) does not yet match the best results we have seen in ALPHA-2 (30 atoms/mixing). This is unsurprising, given the many years of development on ALPHA-2. The ALPHA-g performance was adequate for the first attempts at systematic studies in 2022.

The experimental protocol for determining the direction of the gravitational force on antimatter involves accumulating antihydrogen atoms for some time and then releasing them axially by ramping down the current in the mirror coils. The magnet assembly is illustrated in Figure 7. Gravity should be detectable as a difference between the number of atoms escaping to the bottom and the number escaping to the top, as detected by the TPC annihilation detector. Of course, this experiment requires precise control and characterization of the magnetic fields in the experiment. For example, the 'normal' (*i.e.,* for hydrogen) gravitational potential energy difference between the top and bottom (~256 mm) of the antihydrogen trap is equivalent to a magnetic field difference of 0.45 mT acting on the dipole moment. Compared to this, the ALPHA-g magnet system, which features a high-precision DC current transformer used in a feedback loop to regulate the power supply current, can control the difference in the mirror coil currents at the level of 0.01*g*.

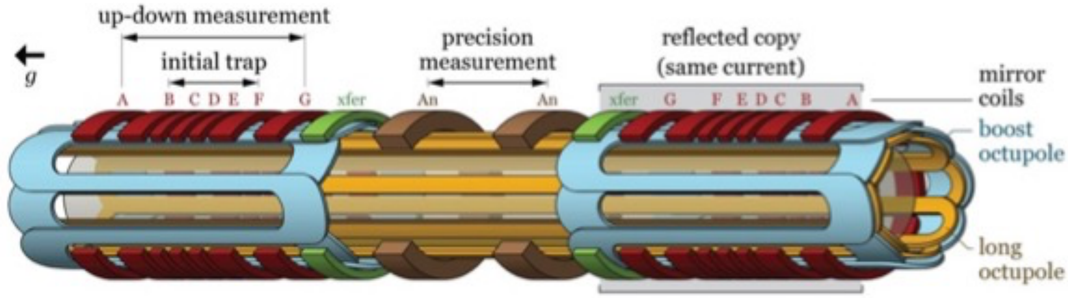

Figure 7. The magnet assembly for ALPHA-g. In 2022, the trap labelled 'up-down measurement' was employed, along with the long octupole. The trapped anti-atoms were released by ramping down the current in mirror coils A and G. The trap is oriented vertically in the cryostat; the top is to the right in this figure; the arrow represents the direction of 'normal' gravity.

Note that the mirror coils (A and G) are connected in series for the studies in 2022, but we can apply a differential or 'bias' current to one of the mirrors. We can in principle employ the bias field as a variable to make a more detailed study of gravitation than by just releasing the atoms from a symmetric trap. Figure 7 shows simulated data of the type that were used to inform the experimental approach. The plot shows the fraction of particles that exit at the bottom of the trap as a function of the magnetic bias applied to the mirror coils. Curves are shown for normal gravity (red) and for three other illustrative values of the gravitational acceleration: 0.5*g* (light green), 0*g* (turquoise), and -1*g* ('anti-gravity', blue). In a one-dimensional model, where we consider only particles on axis, 'normal' gravity would imply that 50% of the particles exit downwards for an applied bias of -1*g* – about 0.45mT field difference between the mirrors. The simulation is a full three-dimensional model and these curves are for a 20 s ramp-down time.

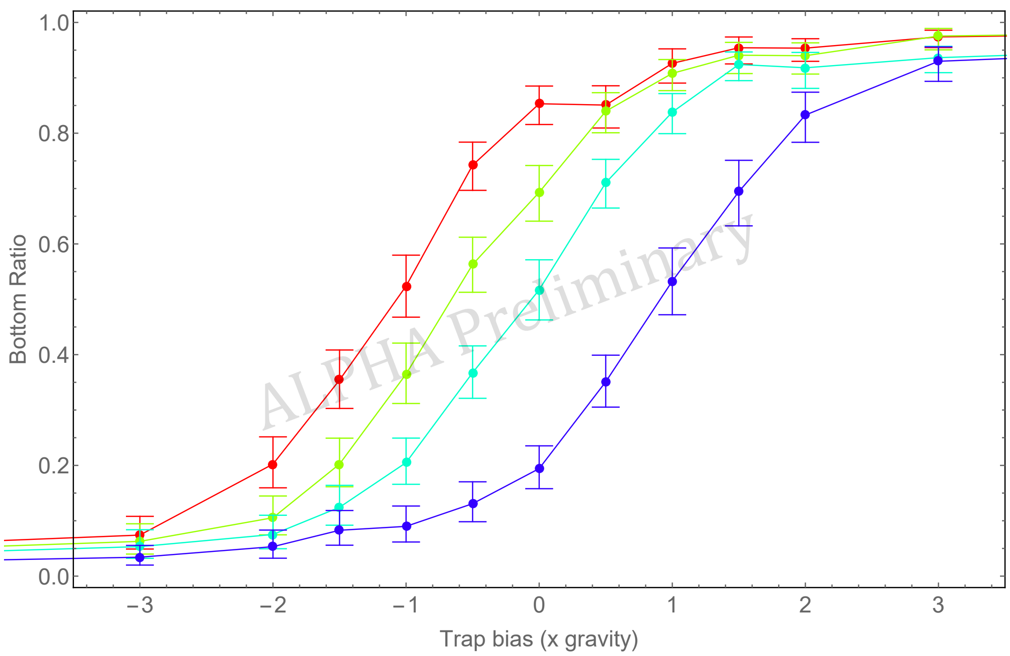

Figure 8. Simulated release data: the fraction of anti-atoms escaping at the bottom is plotted as a function of the magnetic trap bias for four different values of gravitational acceleration. See the text.

These typical 's-curves' are central to the understanding the experimental strategy of ALPHA-g. For future experiments, to determine the magnitude of *g-bar* with high precision, a general figure of merit is the steepness of the transition region between 0 and 1 of this curve. Note that we will also be able to implement laser cooling in ALPHA-g. This is expected to have a profound effect, which we are currently attempting to quantify through simulations informed by our experience in 2022. The necessary hardware is already in place, but we did not have time to introduce the laser in the experiment in 2022.

Figure 9 illustrates a proof-of-principle of the release experiments. Here, only one mirror coil was ramped down at a time, forcing the particles to exit at only one end of the trap. The experimental data are compared to simulations. The detector spatial resolution is not modelled in the simulation. In fact, advances in the reconstruction algorithm of the annihilation have led to significant improvement in the z-resolution of the TPC.

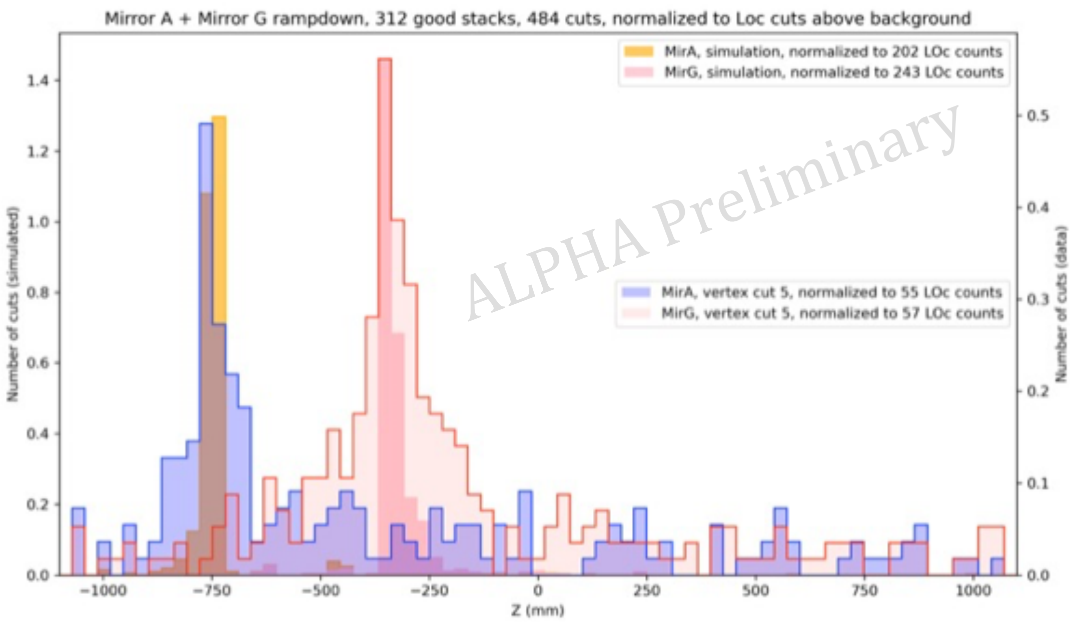

Figure 9. Experimental and simulated distributions of antihydrogen atoms released by ramping down only one mirror coil at a time. A gravity-sensitive experiment requires both coils to be ramped down in tandem.

The figure illustrates that we can clearly distinguish between the up and down distributions.

The collaboration is currently analyzing all of the gravitation data from the 2022 run and is therefore not prepared to report on the results at this time.

3. Magnetic field measurements in ALPHA-g

As stated above, precise control and knowledge of the magnetic field are essential to the interpretation of our experimental results. We have previously discussed using trapped electron plasmas and electron cyclotron resonance[2] measurements to determine our fields. The ECR method has sub-ppm precision at 1 T, but the measurements take about 30s for a single axial point. Figure 10 shows a typical field map with the antihydrogen trap energized.

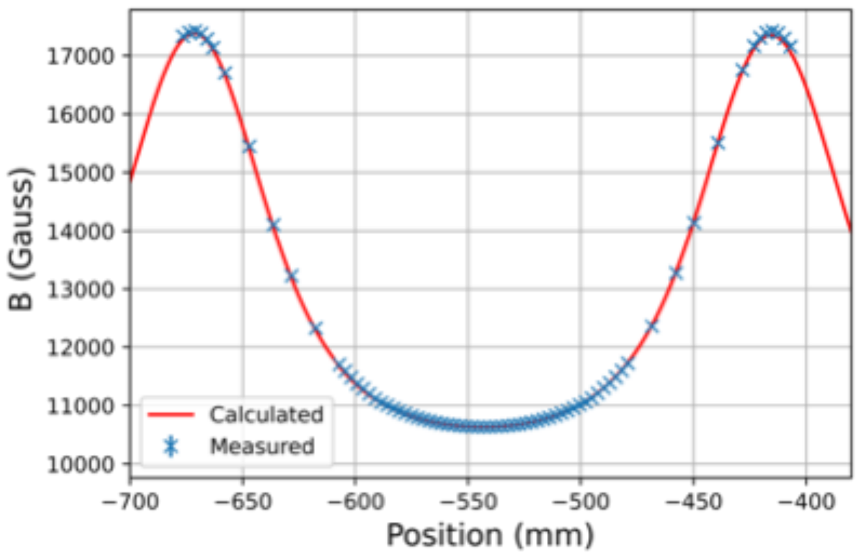

Figure 10. The on-axis field in the antihydrogen trap, measured using ECR. The uncertainties are invisible on this scale.

For understanding the dynamic evolution of the fields, we have developed a new technique which involves measurement of the magnetron frequency of electron plasmas in the trapping region. This technique can measure a field point in about 50 ms, but the precision is of order 10^{-4} T. This technique is particularly useful in studying induced or persistent fields in the superconducting coils. In concert with the ECR technique, these measurements can give us a very complete picture of the fields during the ramp-down. These methods will be of increasing importance for the future precision measurements of the magnitude of g-bar.

4. Sympathetic cooling of positrons by laser-cooled Be ions.

Following our initial ultra-cold positron results in 2020, where we used laser-cooled Beryllium ions to sympathetically cool a positron plasma, we have worked towards integrating this process with antihydrogen formation. This requires it to be robust, reproducible, and preferably compatible with the existing cycle of antihydrogen trapping and accumulation. Due to the ongoing ALPHA-g work we have not worked with positrons, but have focussed on making Beryllium loading and cooling more robust. To accomplish this we have added an axial laser path using mirrors on the upstream and downstream diagnostic stations for Alpha-2, which now allows us to laser-cool Beryllium anywhere in the Alpha-2 trap system, as opposed to before where laser-cooling could only take place in the central electrodes.

Using this new upgraded we have successfully implemented our SDR-EVC[3] (strong drive rotating wall – evaporative cooling) technique on Be+ ions, the first time it's been used on ions and a key step towards stabilising and controlling the number of cold Be+ ions used in the sympathetic cooling process. Figure 1 shows the result of applying SDR-EVC on laser-cooled Be+ ions. The improved control of the ions has allowed us to consistently achieve very low Be+ plasma temperatures, as measured using the parallel energy analyser technique.

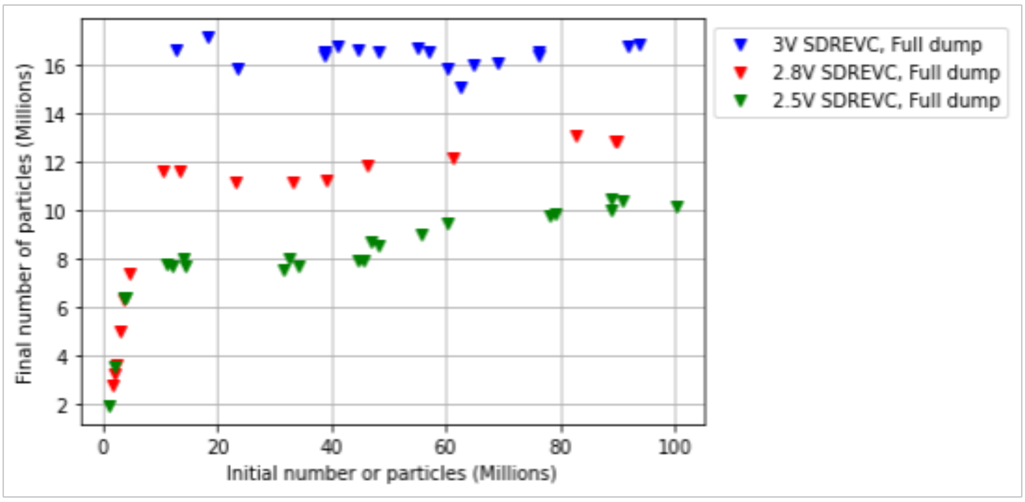

Figure 11. Final number of Be+ ions versus the initial number loaded after three different types of SDR-EVC experiment. Note how most variation in number is eliminated by the procedure.

In a separate development we have tested the use tof he above Be+ plasmas for magnetometry, crucial to ALPHA-g but also increasingly important in ALPHA-2. The experiment consists of exploiting the fact that a laser-cooled Be+ ion can be sent to a so-called dark state using a microwave pulse.This state is only slowly re-pumped to the laser-cooling transition and a loss of fluorescence can therefore be observed if the hyperfine transition to the dark state is triggered. This hyperfine transition, which can be induced by microwaves, is highly dependent on magnetic field and well understood, meaning that there is a great potential for very precise measurements of magnetic field in a fashion complementary to our traditional ECR measurements. In addition the hyperfine transition is sensitive to the magnetic field strength of the microwaves, thus it probes a complementary component of the electro-magnetic field which could be used for better understanding the hyperfine transitions we observer and measure in antihydrogen. Figure 12 shows the comparison of a first set of measurements using this technique with our current standard ECR technique demonstrating the capability. We expect with improved control and diagnostics that this will be a very powerful tool for future precision and gravity measurements.

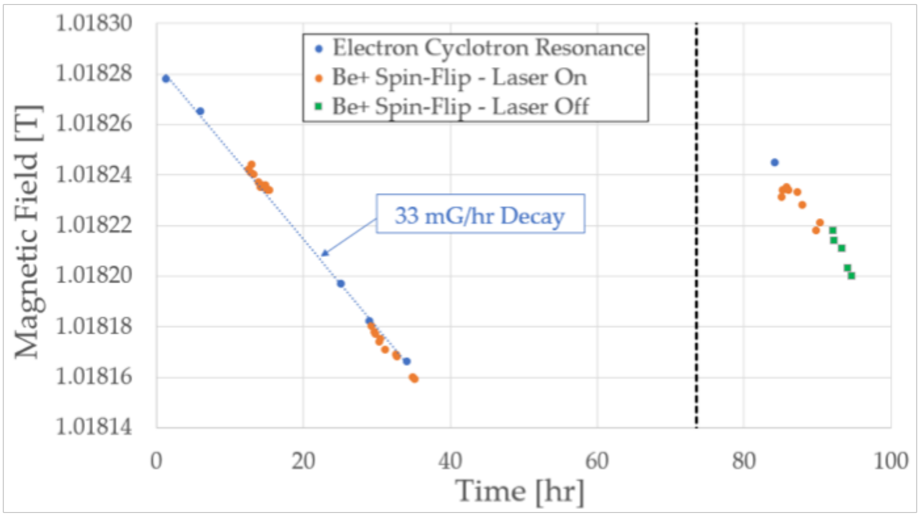

Figure 12 : Magnetic field in the centre of Alpha-2 measured using either the ECR technique (blue dots) or one of two different ways to do the Be+ spin flip technique. The decay observed is the natural decay of the persistent field of the Alpha-2 main solenoid. The black dashed vertical line indicates the time when the nearby main solenoid for Alpha-g was energised.

5. Outlook

We will prioritize ALPHA-2 and spectroscopy in 2023. In fact, we are hoping to upgrade the cooling system for the ALPHA-g solenoid during early 2023. This requires a major intervention and disassembly of the entire apparatus. Currently we are waiting for confirmation of the availability of the new cryocoolers from Sumitomo. We hope to begin this intervention in March of 2023. ALPHA-g would in principle be available for the 2023 run, but we have a full physics program with ALPHA-2 in any event.

As mentioned above, we have yet to do a really systematic optimization of the laser cooling procedure in ALPHA-2. For example, the cooling is expected to saturate at some time due to the spontaneous emission heating. The transverse heating is only balanced by dynamic mixing of the motional degrees of freedom, as the laser cooling is only longitudinal. The time scale for this mixing has been studied by simulation, but real experiments are needed to understand these effects. There may be indications of this saturation already in the 2022 detuning data, but this needs to be further investigated.

The next step is to fully explore the impact of laser cooling on our spectroscopic measurements. The main impact of laser cooling on the 1s-2s linewidth should be in the transit-time broadening. However, colder particles will explore less of the trap volume and thus experience smaller magnetic field variations. Again, we have simulated these effects but have yet to explore them experimentally. In principle, after laser cooling, the magnetic trap depth can be reduced, again reducing the large magnetic field gradients. Given that the accumulation of several thousand trapped atoms has been demonstrated, we can probably afford to dump the more energetic ones in order to use very shallow wells.

In 2023, we will also operate the experiment with our new metrology capabilities – the hydrogen maser and the cesium fountain clock. It is difficult to predict what will limit the precision of the 1s-2s frequency determination in 2023, but it is clear that we could use the entire beamtime on just this experiment.

Also on the agenda is a more precise determination of the ground state hyperfine splitting frequency and the magnetic moment. We have unpublished data at the 10ppm precision level here, and we believe that we can improve this. The magnetic field measurement methodology developed for ALPHA-g will contribute to improving this measurement.

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[1] Baker, C.J. *et al.* Laser cooling of antihydrogen atoms. *Nature* ***592****,* 35–42 (2021).
[2] *In situ electromagnetic field diagnostics with an electron plasma in a Penning–Malmberg trap* (ALPHA Collaboration) New J. Phys. **16** (2014).
[3] Ahmadi, M. et al. Enhanced control and reproducibility of non-neutral plasmas. *Phys. Rev. Lett*. **120**, 025001 (2018).