Final Report:

Advanced Accelerator Concepts

Department of Energy Grant DE-FG02-04ER41289

Principal Investigator:

Professor Jonathan S. Wurtele

Department of Physics
366 Le Conte Hall,
University of California, Berkeley
Berkeley, CA 95720
wurtele@berkeley.edu
510-643-1575

co-Principal Investigator
Professor Joel Fajans
Department of Physics
University of California, Berkeley

Period: April 2009-September 2012

Advanced Accelerator Concepts Final Report

Overview A major focus of research supported by this Grant has been on the ALPHA antihydrogen trap. We first trapped antihydrogen in 2010 [1] and soon thereafter demonstrated trapping for 1000s [2]. We now have observed resonant quantum interactions with antihydrogen [3]. These papers in Nature [1, 3] and Nature Physics [2] report the major milestones in anti-atom trapping. The success was only achieved through careful work that advanced our understanding of collective dynamics in charged particle systems, the development of new cooling and diagnostics, and innovation in understanding how to make physics measurements with small numbers of anti-atoms. This research included evaporative cooling [4], autoresonant excitation[5] of longitudinal motion, and centrifugal separation[6].

Antihydrogen trapping by ALPHA is progressing towards the point when a important theories believed by most to hold for all physical systems, such as CPT (Charge-Parity-Time) invariance and the Weak Equivalence Principle (matter and antimatter behaving the same way under the influence of gravity) can be directly tested in a new regime. One motivation for this test is that most accepted theories of the Big Bang predict that we should observe equal amounts of matter and antimatter. However astrophysicists have found very little antimatter in the universe. Our experiment will, if successful over the next seven years, provide a new test of these ideas. Many earlier detailed and beautiful tests have been made, but the trapping of neutral antimatter allows us to explore the possibility of direct, model-independent tests. Successful cooling of the anti atoms, careful limits on systematics and increased trapping rates, all planned for our follow-up experiment (ALPHA-II) will reach unrivaled precision. CPT invariance implies that the spectra of hydrogen and antihydrogen should be identical. Spectra can be measured in principle with great precision, and any differences we might observe would revolutionize fundamental physics. This is the physics motivation for our experiment, one that requires only a few dozen researchers but must effectively integrate plasma, accelerator, atomic, and fundamental physics, as well as combine numerous technologies in the control, manipulation, and measurement of neutral and non-neutral particles.

The ELENA ring [7, 8] (to which we hope to contribute, should funding be provided) is expect, when completed, to significantly enhance the performance of antihydrogen trapping by increasing by a factor of 100 the number of antiprotons that can be successfully trapped and cooled. ELENA operation is scheduled to commence in 2017.

In collaboration with LBNL scientists, we proposed [9] a frictional cooling scheme. This is an alternative cooling method to that used by ELENA. It is less complicated, experimentally unproven, and produces a lower yield of cold antiprotons.

Students and postdoctoral researchers work on the trapping, cooling, transport, and nonlinear dynamics of antiprotons bunches that are provided by the AD to ALPHA; they contribute to the operation of the experiment, to software development, and to the design and operation of experiments. Students are expected to spend at summers at CERN while taking courses; after completion of courses they typically reside at CERN for most of the half-year run. The Antiproton Decelerator [AD] at CERN, along with its experiments, is the only facility in the world where antiprotons can be trapped and cooled and combined with positrons to form cold antihydrogen, with the ultimate goal of studying CPT violation and, subsequently, gravitational interactions of antimatter.

Outreach/Publicity/Recognition: ALPHA's recent success in trapping antihydrogen attracted worldwide attention:

1. Deemed the top breakthrough (*physicsworld.com/cws/article/news/44618*) in 2010 by *Physics World*/Institute of Physics (shared honors with another, more limited success achieved by the ASACUSA collaboration);
2. The trapping paper was the "most clicked news and feature of 2010" in *Nature* (*www.nature.com/news/specials/2010/reader-topten.html*);
3. Inclusion in the unranked list of "Top Ten Physics-Related News Stories of 2010" of the American Physical Society (*www.aps.org/publications/apsnews/201102/toptennews.cfm*);
4. *Science* Magazine wrote (*www.sciencemag.org/content/330/6011/1625.2.full*): "CERN physicists' success in trapping atoms of antihydrogen, reported in November, also justifiably impressed readers. We passed it over [for Breakthrough of the Year] only because it's sure to be quickly overshadowed by follow-up experiments to measure critical properties of the mysterious antimatter...."
5. Over 800 newspaper accounts listed on *Google* News, and briefly listed as the top news story (on all topics, not just science) in the world by *Google* News;
6. A graphic of the ALPHA magnetic trap, made by Chukman So, a graduate student supported by the grant, appeared on the cover of the January 2011 *CERN Courier*; another of his graphics was used for the cover of *Nature Physics* in July 2011.

Beyond the ALPHA experiment, the group worked on beam physics problems including limits on the average current in a time-dependent period cathode [10, 11] and new methods to create longitudinally coherent high repetition rate soft x-ray sources [12] and wide bandwidth mode locked x-ray lasers[13]. We completed a detailed study of quantum mechanical effects in the transit time cooling of muons

We contributed three white papers at the *Accelerators for America Workshop* [8, 14, 15] on accelerators for low energy antiprotons [8] and high-energy density science [14] and modeling accelerators for future X-ray FELs [15] and a paper at the Intensity Frontier Workshop [16].

I. RESEARCH PROGRESS

Antihydrogen trapping has been a topic of research supported by this Grant [1–6, 9, 16–22]. Beam physics ideas and techniques play an important role in the success of the experiment and the experiment has motivated some beam physics ideas. Our papers include trap operation and techniques, matching the AD output into our experiment, electron cooling of hot antiprotons, transport of charged particle bunches without heating, evaporative cooling, centrifugal separation, manipulation of antiproton phase space with autoresonant excitation, frictional cooling, and physics studies on trapped anti atoms.

Trapping and Probing of Antihydrogen: In 2010 the ALPHA collaboration at CERN reported trapping 38 atoms of antihydrogen. [1]. This was the first time that neutral antimatter has ever been trapped. Since the initial report, over 300 antihydrogen atoms have been trapped, and thousand-second trapping times have been observed. This result was a very significant milestone towards measurements that can have significant impact on our understanding of nature. We continued work for another two years and demonstrated, in a report published in 2012 in Nature [3] that, even with only one trapped atom per attempt (when the apparatus is working well), we can induce and observe a resonant quantum transition in antihydrogen.

Ours is the first spectroscopy of a pure antimatter atom. After trapping an atom for time long enough to be almost certain that it is in the ground state we applied microwaves on and off the transition frequency to between the Zeeman-shifted hyperfine levels of the ground state of antihydrogen. We flipped the positron spin, thereby changing the anti-atom from a low-field seeking state to a high-field seeking state. As a result, the anti-atom hit the trap wall and the resulting pions were was observed by our time and position sensitive detector. The resonant nature of the interaction was confirmed by comparing the survival rate of trapped antihydrogen irradiated with on-resonance microwaves to that of exposed to off-resonance microwaves. This ALPHA study [3] found 23 antihydrogen atoms that survived in 110 trapping attempts using off-resonance microwaves (0.21 per 15 attempt), but only two atoms that survived in 103 attempts with on-resonance microwaves (0.02 per attempt).

Rather than give an overly brief description of each paper, we emphasize the thesis research of a graduate student in our group.

Antihydrogen is comprised of an antiproton and a positron and is created when low temperature plasmas of antiprotons and positrons are mixed in a nested Penning-Malmberg. The two species must be mixed together without introducing excessive kinetic energy. Otherwise all the antihydrogen will escape from our atom trap. The confinement of the neutral antihydrogen relies not on charge but spin, and is realized by superimposing on the nested Penning-Malmberg trap a magnetic minimum configuration, consisting of an octupole field for radial confinement and two mirror fields for axial confinement. A successful mixing process must be robust to both shot-shot fluctuating space-charge forces and electronic noise on the electrodes that control the axial motion and radial compression. Further, it must not impart too much kinetic energy to the antiprotons. A schematic of the potentials and geometry is in Fig. 1.

The antiproton and positrons, prior to mixing, are trapped in adjacent potential wells (note that the species are oppositely charged so that antiprotons seek high potential regions while the positrons seek low potential). ALPHA adopted the autoresonant injection technique [5], where the antiprotons (typically a few tens of thousands in number) are manipulated by an oscillating electrode voltage which creates a small perturbation to the antiproton well at a frequency initially above the antiproton bounce frequency. The perturbation's frequency is then slowly decreased through the antiproton linear resonance frequency. Positrons, with a higher oscillation frequency and located further away from the drive electrode, respond quasi-statically. Antiprotons pick up energy from the driving field via autoresonant phase-locking to the chirped drive.

To better understand and to improve upon this complex and non-linear injection scheme, we developed a numerical Vlasov-Poisson solver. A Fokker-Plank dissipation and diffusion term is also included to model the cooling on the antiprotons on the positrons as they mix together to form antihydrogen. The simulation follows coupled 1D Vlasov distribution functions in each radial shell. The radial coupling is through the Poisson equation; particles are confined to a fixed radius on the time-scales of interest, by the strong applied magnetic field. A similar model for two-dimensional BGK-like modes in nonneutral plasmas proved successful in earlier numerical studies in our group [23–25]. A quasi-static Poisson-Boltzmann positron potential is included along with the external and self-consistent antiproton potentials in the Vlasov equation.

Fundamental Beam Physics and Radiation Generation The Child-Langmuir law limits the steady-state current density across a one-dimensional planar diode. It is well-known that the peak current density can surpass this limit when the boundary conditions vary in time, it remains an open question of whether the average current can violate the Child-Langmuir limit under time-dependent conditions. We studied [11] the case where the applied voltage is constant but the electric field at the cathode, and hence the charge, is allowed to vary periodically in time. One-dimensional particle-in-cell simulations indicate that such a violation is impossible and we conjectured such an upper bound on the time-averaged current density. This work stimulated numerous papers which seek formal limits on the average current obtainable from time-dependent cathode emission. More recently, in response to this ongoing discussion of this problem, we slightly amended our conjecture [10] and the discussion continues.

Concepts for phase space control were applied to a new beam-wiggler configuration for a soft x-ray oscillators. This work progressed to the point where it was supported by LBL LDRD funds. We presented [12] numerous conceptual configurations for soft x-ray oscillators at the 2010 FEL conference and subsequently a graduate student pursued a specific modified geometry at a more detailed level of analysis (paper in preparation). We proposed and studied [13] a new scheme for

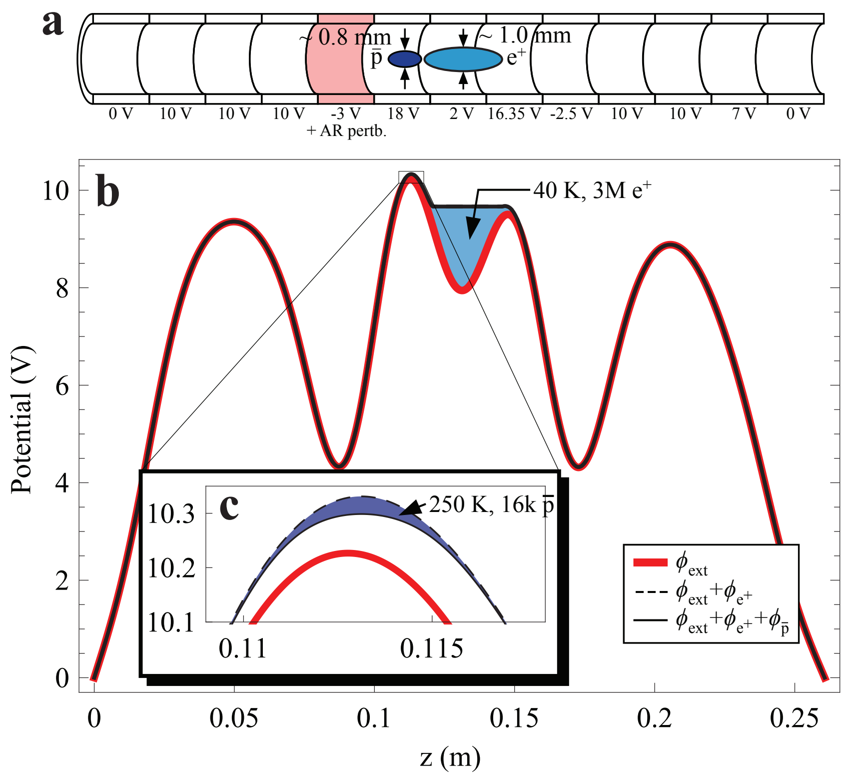

FIG. 1: Potentials and geometry for injecting antiprotons into positrons. (a) The physical setup of the experiment, with the pink electrode connected to the AR signal generator. (b) The external potential created by the electrodes at $r = 0$, and the effect of the positron space charge. (c) A close–up of b, showing the effect of the antiproton space charge.

mode locking a free-electron laser (FEL) amplifier based on electron beam current modulation. Illustrative examples using a hypothetical mode-locked FEL amplifier were given and the ability to generate intense coherent radiation with a large bandwidth demonstrated. We also collaborated [26] with scientists at the Heavy Ion Fusion Virtual National Laboratory to examine ion beam driven high energy density physics. We wrote one paper [27] on a comparison of modified three-wave codes with particle-in-cell simulations and contributed to studies of kinetic effects on RBS [28, 29], studied two-dimensional effects in RBS compression [30] and pioneered the use of autoresonance to understand [31] the nonlinear saturation of RBS in plasmas with density gradients.

We developed [32] a detailed analysis on quantum effects in optical stochastic cooling. This paper is well-summarized by its abstract [32]: Ultra-fast stochastic cooling would be desirable in certain applications, for example, in order to boost final luminosity in a muon collider or neutrino factory, where short particle lifetimes severely limit the total time available to reduce beam phase space. But fast cooling requires very high-bandwidth amplifiers so as to limit the incoherent heating effects from neighboring particles. A method of transit-time optical stochastic cooling has been proposed which would employ high-gain, high-bandwidth, solid-state lasers to amplify the spontaneous radiation from the charged particle bunch in a strong-field magnetic wiggler. This amplified light is then fed back onto the same bunch inside a second wiggler, with appropriate phase delay to effect cooling. But before amplification, the usable signal from any one particle is quite small, on average much less than one photon per pass, suggesting that the radiation should be treated quantum mechanically, and raising doubts as to whether this weak signal even contains sufficient phase information necessary for cooling, and whether it can be reliably amplified to provide the expected cooling on each pass. A careful examination of the dynamics, where the radiation and amplification processes are treated quantum mechanically, indicates that fast cooling is in principle possible, with cooling rates which essentially agree with classical calculations, provided that the effects of the unavoidable amplifier noise are included. Thus, quantum mechanical uncertainties do not present any insurmountable obstacles to optical cooling, but do establish a lower limit on cooling rates and achievable emittances.

Undergraduate Research: Undergraduates from our group conduct research on antihydrogen traps, the Muon Ionization Cooling Experiment in the UK, laser-plasma acceleration and fundamentals of radiation generation. At the close of the Grant four Berkeley undergraduates, including an exchange student from Ireland, were conducting research under the auspices of the Grant. Undergraduates have been lead or second authors on refereed publications [13, 27]. Two Berkeley undergraduates, working under supervision of the PI and visiting Prof. Dan Kaplan, conducted simulations for the MICE experiment at RAL and spent time at RAL in the Summer of 2012.

---

[1] G. B. Andresen, M. D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P. D. Bowe, E. Butler, C. L. Cesar, S. Chapman, M. Charlton, A. Deller, S. Eriksson, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, A. J. Humphries, R. Hydomako, M. J. Jenkins, S. Jonsell, L. V. Jorgensen, L. Kurchaninov, N. Madsen, S. Menary, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, S. Seif el Nasr, D. M. Silveira, C. So, J. W. Storey, R. I. Thompson, D. P. van der Werf, J. S. Wurtele, and Y. Yamazaki. Trapped antihydrogen. *Nature*, 468(7324):673–676, 12 2010.

[2] G. B. Andresen, M. D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P. D. Bowe, E. Butler, C. L. Cesar, S. Chapman, M. Charlton, A. Deller, S. Eriksson, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, A. J. Humphries, R. Hydomako, M. J. Jenkins, S. Jonsell, L. V. Jorgensen, L. Kurchaninov, N. Madsen, S. Menary, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, S. Seif el Nasr, D. M. Silveira, C. So, J. W. Storey, R. I. Thompson, D. P. van der Werf, J. S. Wurtele, and Y. Yamazaki. Confinement of antihydrogen for 1,000 seconds. *Nature Physics*, 7(7):558–564, 07 2011.

[3] C. Amole, M. D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P. D. Bowe, E. Butler, A. Capra, C. L. Cesar, M. Charlton, A. Deller, P. H. Donnan, S. Eriksson, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, A. J. Humphries, C. A. Isaac,

S. Jonsell, L. Kurchaninov, A. Little, N. Madsen, J. T. K. McKenna, S. Menary, S. C. Napoli, P. Nolan, K. Olchanski, A. Olin, P. Pusa, C. O. Rasmussen, F. Robicheaux, E. Sarid, C. R. Shields, D. M. Silveira, S. Stracka, C. So, R. I. Thompson, D. P. van der Werf, and J. S. Wurtele. Resonant quantum transitions in trapped antihydrogen atoms. *Nature*, 483(7390):439–443, 03 2012.

[4] G. B. Andresen, M. D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P. D. Bowe, E. Butler, C. L. Cesar, S. Chapman, M. Charlton, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, J. S. Hangst, W. N. Hardy, R. S. Hayano, M. E. Hayden, A. Humphries, R. Hydomako, S. Jonsell, L. Kurchaninov, R. Lambo, N. Madsen, S. Menary, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, D. M. Silveira, C. So, J. W. Storey, R. I. Thompson, D. P. van der Werf, D. Wilding, J. S. Wurtele, and Y. Yamazaki. Evaporative cooling of antiprotons to cryogenic temperatures. *Phys. Rev. Lett.*, 105(1):013003, Jul 2010.

[5] G. B. Andresen, M. D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P. D. Bowe, E. Butler, P. T. Carpenter, C. L. Cesar, S. Chapman, M. Charlton, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, J. S. Hangst, W. N. Hardy, M. E. Hayden, A. J. Humphries, J. L. Hurt, R. Hydomako, S. Jonsell, N. Madsen, S. Menary, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, D. M. Silveira, C. So, J. W. Storey, R. I. Thompson, D. P. van der Werf, J. S. Wurtele, and Y. Yamazaki. Autoresonant excitation of antiproton plasmas. *Phys. Rev. Lett.*, 106(2):025002, Jan 2011.

[6] G. B. Andresen, M. D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P. D. Bowe, E. Butler, C. L. Cesar, S. Chapman, M. Charlton, A. Deller, S. Eriksson, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, A. J. Humphries, R. Hydomako, S. Jonsell, N. Madsen, S. Menary, P. Nolan, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, D. M. Silveira, C. So, J. W. Storey, R. I. Thompson, D. P. van der Werf, J. S. Wurtele, and Y. Yamazaki. Centrifugal separation and equilibration dynamics in an electron-antiproton plasma. *Phys. Rev. Lett.*, 106:145001, Apr 2011.

[7] ELENA Collaboration. An upgrade to the antiproton decelerator. *CERN-SPSC-2009-026 / SPSC-P-338*, 2009.

[8] J. Fajans, G. Gabielse, F. Robicheaux, A. M. Sessler, and J. S. Wurtele. Discovery science with low energy antiproton sources: The ELENA upgrade,. *White Paper, Accelerators for America Symposium*, 2009.

[9] M. Zolotorev, A. Sessler, G. Penn, J. S. Wurtele, and A. E. Charman. Enhancing trappable antiproton populations through deceleration and frictional cooling. *Phys. Rev. ST Accel. Beams*, 15:033502, Mar 2012.

[10] M. E. Griswold, N. J. Fisch, and J. S. Wurtele. Amended conjecture on an upper bound to time-dependent space-charge limited current. *Physics of Plasmas*, 19(2):024502, 2012.

[11] M. E. Griswold, N. J. Fisch, and J. S. Wurtele. An upper bound to time-averaged space-charge limited diode currents. *Physics of Plasmas*, 17(11):114503, 2010.

[12] J. S. Wurtele, K. J. Kim, R. R. Lindberg, A. A. Zholents, G. E. Penn, M. Reinsch, P. R. Gandhi, and X.W. Gu. Tunable soft x-ray oscillators. *Proceedings of the 2010 Free Electron Laser Conference (Invited)*, 2010.

[13] E Kur, D J Dunning, B W J McNeil, J Wurtele, and A A Zholents. A wide bandwidth free-electron laser with mode locking using current modulation. *New Journal of Physics*, 13(6):063012, 2011.

[14] J. S. Wurtele, J. J. Barnard, R. C. Davidson, R. W. Falcone, R. W. Lee, J.B. Hastings, H-J Lee, and B.G. Logan. Discovery potential of high energy density science including warm dense matter. *White*

Paper, Accelerators for America Symposium, 2009.

[15] R. Ryne, M. Borland, B. Carlsten, J. N. Corlett, D. Douglas, W. M. Fawley, G. Krafft, J Qiang, J.L. Vay, M. Venturini, J. S. Wurtele, and A. A. Zholents. Accelerator modeling for future fel-based light sources. *White Paper Accelerators for America Workshop*, 2009.

[16] J. Fajans, F. Robicheaux, J.S. Wurtele, and others (ALPHA Collaboration). Antihydrogen research on ALPHA. In J.L. Hewett et al., editors, *Fundamental Physics at the Intensity Frontier*. arXiv 1205.2671, 2012.

[17] G B Andresen, M D Ashkezari, M Baquero-Ruiz, W Bertsche, P D Bowe, E Butler, C L Cesar, S Chapman, M Charlton, A Deller, S Eriksson, J Fajans, T Friesen, M C Fujiwara, D R Gill, A Gutierrez, J S Hangst, W N Hardy, M E Hayden, A J Humphries, R Hydomako, M J Jenkins, S Jonsell, L V JØrgensen, L Kurchaninov, N Madsen, J T K McKenna, S Menary, P Nolan, K Olchanski, A Olin, A Povilus, P Pusa, F Robicheaux, J Sampson, E Sarid, D Seddon, S Seif el Nasr, D M Silveira, C So, J W Storey, R I Thompson, J Thornhill, D Wells, D P van der Werf, J S Wurtele, and Y Yamazaki. The alpha – detector: Module production and assembly. *Journal of Instrumentation*, 7(01):C01051, 2012.

[18] C Amole, G B Andresen, M D Ashkezari, M Baquero-Ruiz, W Bertsche, E Butler, C L Cesar, S Chapman, M Charlton, A Deller, S Eriksson, J Fajans, T Friesen, M C Fujiwara, D R Gill, A Gutierrez, J S Hangst, W N Hardy, M E Hayden, A J Humphries, R Hydomako, L Kurchaninov, S Jonsell, N Madsen, S Menary, P Nolan, K Olchanski, A Olin, A Povilus, P Pusa, F Robicheaux, E Sarid, D M Silveira, C So, J W Storey, R I Thompson, D P van der Werf, and J S Wurtele. Discriminating between antihydrogen and mirror-trapped antiprotons in a minimum-B trap. *New J. Phys.*, 14:015010, 2012.

[19] G.B. Andresen, M.D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P.D. Bowe, C.C. Bray, E. Butler, C.L. Cesar, S. Chapman, M. Charlton, J. Fajans, T. Friesen, M.C. Fujiwara, D.R. Gill, J.S. Hangst, W.N. Hardy, R.S. Hayano, M.E. Hayden, A.J. Humphries, R. Hydomako, S. Jonsell, L.V. Jorgensen, L. Kurchaninov, R. Lambo, N. Madsen, S. Menary, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, S. Seif El Nasr, D.M. Silveira, C. So, J.W. Storey, R.I. Thompson, D.P. van der Werf, D. Wilding, J.S. Wurtele, and Y. Yamazaki. Search for trapped antihydrogen. *Physics Letters B*, 695(1-4):95 – 104, 2011.

[20] E. Butler, G.B. Andresen, M.D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P.D. Bowe, C.C. Bray, C.L. Cesar, S. Chapman, M. Charlton, J. Fajans, T. Friesen, M.C. Fujiwara, D.R. Gill, J.S. Hangst, W.N. Hardy, R.S. Hayano, M.E. Hayden, A.J. Humphries, R. Hydomako, S. Jonsell, L. Kurchaninov, R. Lambo, N. Madsen, S. Menary, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, D.M. Silveira, C. So, J.W. Storey, R.I. Thompson, D.P. Werf, D. Wilding, J.S. Wurtele, and Y. Yamazaki. Towards antihydrogen trapping and spectroscopy at alpha. *Hyperfine Interactions*, 199(1-3):39–48, 2011.

[21] G. B. Andresen, W. Bertsche, C. C. Bray, E. Butler, C. L. Cesar, S. Chapman, M. Charlton, J. Fajans, M. C. Fujiwara, D. R. Gill, W. N. Hardy, R. S. Hayano, M. E. Hayden, A. J. Humphries, R. Hydomako, L. V. Jorgensen, S. J. Kerrigan, J. Keller, L. Kurchaninov, R. Lambo, N. Madsen, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, S. Seif El Nasr, D. M. Silveira, J. W. Storey, R. I. Thompson, D. P. van der Werf, J. S. Wurtele, and Y. Yamazaki ALPHA Collaboration. Magnetic multipole induced zero-rotation frequency bounce-resonant loss in a penning–malmberg trap used for antihydrogen trapping. *Physics of Plasmas*, 16(10):100702, 2009.

[22] G.B. Andresen, W. Bertsche, P.D. Bowe, C. Bray, E. Butler, C.L. Cesar, S. Chapman, M. Charlton,

J. Fajans, M.C. Fujiwara, D.R. Gill, J.S. Hangst, W.N. Hardy, R.S. Hayano, M.E. Hayden, A.J. Humphries, R. Hydomako, L.V. Jorgensen, S.J. Kerrigan, L. Kurchaninov, R. Lambo, N. Madsen, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, S. Seif El Nasr, D.M. Silveira, J.W. Storey, R.I. Thompson, D.P. van der Werf, J.S. Wurtele, and Y. Yamazaki. Antihydrogen formation dynamics in a multipolar neutral anti-atom trap. *Physics Letters B*, 685(2-3):141 – 145, 2010.

[23] L. Friedland, F. Peinetti, W. Bertsche, J. Fajans, and J. Wurtele. Driven phase space holes and synchronized bernstein, greene, and kruskal modes. *Physics of Plasmas*, 11(9):4305–4317, 2004.

[24] F. Peinetti, W. Bertsche, J. Fajans, J. Wurtele, and L. Friedland. Numerical studies of driven, chirped bernstein, greene, and kruskal modes. *Physics of Plasmas*, 12(6):062112, 2005.

[25] F. Peinetti, F. Peano, G. Coppa, and J. Wurtele. Particle-in-cell method for parallel dynamics in magnetized electron plasmas: Study of high-amplitude bgk modes. *Journal of Computational Physics*, 218:102–122, October 2006.

[26] J.J. Barnard, J. Armijo, D.S. Bailey, A. Friedman, F.M. Bieniosek, E. Henestroza, I. Kaganovich, P.T. Leung, B.G. Logan, M.M. Marinak, R.M. More, S.F. Ng, G.E. Penn, L.J. Perkins, S. Veitzer, J.S. Wurtele, S.S. Yu, and A.B. Zylstra. Ion beam heated target simulations for warm dense matter physics and inertial fusion energy. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 606(1-2):134 – 138, 2009. Heavy Ion Inertial Fusion - Proceedings of the 17th International Symposium on Heavy Ion Inertial Fusion.

[27] T.-L. Wang, D. Michta, R. R. Lindberg, A. E. Charman, S. F. Martins, and J. S. Wurtele. Feasibility study for using an extended three-wave model to simulate plasma-based backward raman amplification in one spatial dimension. *Physics of Plasmas*, 16(12):123110, 2009.

[28] R. K. Kirkwood, Y. Ping, S. C. Wilks, P. Meezan, N .and Michel, E. Williams, D. Clark, L. Suter, O. Lander, N. J. Fisch, E. O. Valeo, V. Malkin, D. Turnbull, S. Suckewer, J. S. Wurtele, T. L. Wang, S. F. Martins, C. Joshi, L. Yin, B. J. Albright, H. A. Rose, and K. J. Bowers. Observation of amplification of light by langmuir waves and its saturation on the electron kinetic timescale. *J. Plasma Phys.*, 77(04):521–528, 2010.

[29] Y. Ping, R. K. Kirkwood, T.-L. Wang, D. S. Clark, S. C. Wilks, N. Meezan, R. L. Berger, J. Wurtele, N. J. Fisch, V. M. Malkin, E. J. Valeo, S. F. Martins, and C. Joshi. Development of a nanosecond-laser-pumped raman amplifier for short laser pulses in plasma. *Physics of Plasmas*, 16(12):123113, 2009.

[30] Min Sup Hur and Jonathan S. Wurtele. Two-dimensional simulations of the amplification and focusing of intense laser pulses in the kinetic regime of raman backward amplification in plasmas. *Computer Physics Communications*, 180(4):651 – 655, 2009. Special issue based on the Conference on Computational Physics 2008 - CCP 2008.

[31] P. Khain, L. Friedland, A. G. Shagalov, and J. S. Wurtele. Nonlocal, kinetic stimulated raman scattering in nonuniform plasmas: Averaged variational approach. *Physics of Plasmas*, 19(7):072319, 2012.

[32] A. E. Charman and J. S. Wurtele. Quantum mechanical treatment of transit-time optical stochastic cooling of muons. *arXiv.org:0905.0485v1*, 2009.