

Single-component plasma of photoelectrons

ATRAP Collaboration

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Abstract

Ten-nanosecond pulses of photoelectrons liberated by intense UV laser pulses from a thin gold layer are captured into a single-component plasma that is ideally suited to cool antiprotons (\bar{p}) for antihydrogen (\bar{H}) production. Up to a billion electrons are accumulated using a series of laser pulses, more than are needed for efficient \bar{p} cooling in the large traps now being used for loading \bar{p} for \bar{H} production. The method is demonstrated within an enclosed vacuum space that is entirely at 4 K, and is thus compatible with the exceptional cryogenic vacuum that is desirable for the long-term storage of antihydrogen. The pitfalls of other electron accumulation methods are entirely avoided, including the particle heating and declining efficiency of field emission point loading, and the heat load and contamination of thermionic emission methods.

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The quantum explanation of the surprising photoelectrons that light liberates from a metal surface was one of the early successes of a quantum view of the world [1]. A century later, the many applications of photoelectrons include multi-electron-beam lithography of integrated circuits [2–4], high-brightness electron sources for storage rings [5,6], microwave power sources, short-wavelength free-electron lasers [7], and generating long electron columns in a Malmberg trap [8].

Here we report the first use of short pulses of photoelectrons to quickly and robustly accumulate the large number of electrons needed to collisionally cool antiprotons (\bar{p})—a crucial step for slow \bar{H} production [9–11]. CERN's unique Antiproton Decelerator facility (AD) delivers 5-MeV \bar{p} . These are slowed to the keV energies at which they can be trapped—either in

a thin matter degrader window [12], or in a RFQ decelerator followed by an even thinner window [13]. Collisions of the keV \bar{p} with cold electrons are the crucial last step [14], reducing the \bar{p} energy by as much as a factor of 10^{10} , to temperatures as low as 4.2 K. Once electron-cooled to such a low energy, the \bar{p} can be held while \bar{p} from many successive AD pulses are captured and cooled by the same electrons, to accumulate large numbers of cold \bar{p} [14–16].

In the new method, 10-ns pulses of up to 100 million low-energy photoelectrons are liberated from a thin gold layer by the pulses of an ultraviolet excimer laser, and more than 10 million of these can be captured in a cryogenic Penning trap. The well-controlled accumulation of a billion-electron plasma from successive electron pulses is demonstrated. The method is intrinsically compatible with the exceptionally good cryogenic vacuum that is desirable for \bar{H} experiments, for which a pressure below 5×10^{-17} Torr has been measured using trapped antiprotons as a vacuum gauge [17]. The electron pulses are

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easily controlled because they are precisely synced with the very short laser pulses.

Photoelectrons offer important advantages for cooling \bar{p} compared to electrons loaded with the two other methods used to date. The first method, thermionic emission from a hot filament, can impose a substantial heat load on a cryogenic vacuum system, and the many atom and molecule species that are also emitted can end up as ions in potential wells where they are not wanted. The heat load is avoided in a second method, using an electron beam that tunnels from a field emission point (FEP) in a 4-K environment. However, substantial time is generally required to cool the initially energetic electrons to the trap's central axis, and the typically hundred or more eV electron beam can heat the trapped electrons via collisions. With the field emission method it was thus challenging to robustly and reproducibly accumulate and center substantially more than 10 million electrons. Also, the FEP loading rate decreases in time. The electrons from the FEP follow field lines to strike a tiny spot on an electrode, liberating absorbed gas atoms into the vacuum. Electrons are trapped when they collide with one of these atoms and lose energy within a trapping well. FEP loading thus stops when these crucial atoms have been removed from the spot.

Pulses of 248-nm light come from a KrF excimer laser which delivers up to 18-mJ pulses with approximately 2 MW of peak power, and up to a repetition rate of 250 Hz. A spot size of 6 mm \times 3 mm is sometimes reduced to 3 mm \times 3 mm using an anamorphic prism pair. The pulses are directed along a 1.5-m path, along the axis of a 1 to 3 T superconducting solenoid, into a 4.2-K vacuum enclosure through a sapphire vacuum window with a diameter of 13 mm. The laser is focussed to just illuminate a photocathode that is 6 mm in diameter, and located at the entrance of a series of cylindrical-Penning-trap electrodes (Fig. 1(b)). These electrodes can be biased to form a series of Penning traps (Fig. 2). The electron pulses traveling through the electrodes have initially the 10-ns duration of the laser pulses,

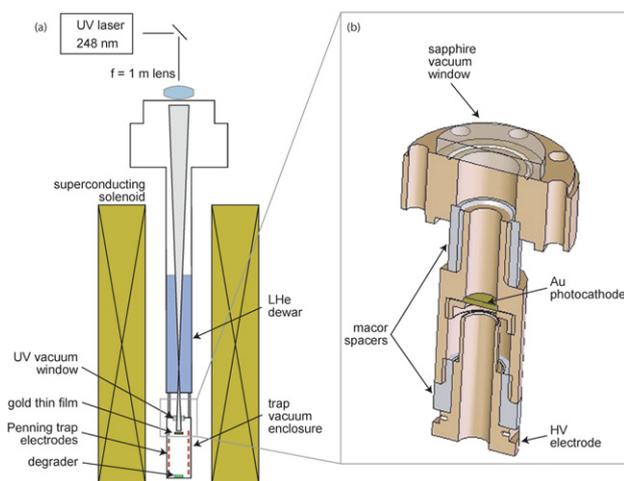


Fig. 1. The excimer laser pulse is directed along the axis of a series of cylindrical Penning trap electrodes (a), through a photocathode that is a thin gold layer on a glass vacuum window (b).

and the number of electrons per pulse increases with laser pulse intensity.

The photocathode is a 15-nm gold film that is evaporated onto a sapphire window, after a 4-nm layer of titanium that reduces the surface instability of the gold [18]. Gold is a good choice, despite a low quantum efficiency of only $\sim 10^{-4}$ (consistent with existing models [4]), for two reasons. First, its photoemission is robust and reproducible even if it spends some time in a modest vacuum or is exposed to air (several days before our installation into vacuum). Second, 5.0-eV photons suffice for the ~ 4.7 -eV work function of gold. Our thickness choice is consistent with another measurement [18], with a model of the quantum efficiency for a solid that includes optical transition probabilities, optical constants and electron inelastic scattering events [19], and also with models that take into account electron–electron scattering, electron–phonon scattering and electron–interface reflection [20,21].

For some measurements, the laser alignment is simplified by delivering the ultraviolet (UV) light through the 1-mm diameter core of hollow fibers, generously provided to us by Matsuura and Miyagi [22–24]. There is thus no fused silica core for the high-intensity laser pulses to damage [25]. Chemical vapor deposition of a thin aluminum layer, employing a metal-organic aluminum as a precursor, eliminates the UV loss of more common, silver-coated hollow fiber. Up to 75% of the incident power could be coupled through a pinhole used to protect the edges of the fiber, and two hollow fibers could be separated with a flat vacuum window with little additional loss. This first demonstration at low temperatures is also potentially of great significance for \bar{H} spectroscopy insofar as 248 nm is close to the 243 nm needed for 2-photon excitation of the \bar{H} 1s–2s transition.

The photoelectrons liberated from the gold cathode (Au in Fig. 2) follow magnetic field lines from it to a flat degrader electrode (DEG in Fig. 2), which has a large positive bias to attract them, and to keep secondary electrons from escaping. The number of electrons arriving at DEG is determined from the integrated charge measured with a calibrated charge-sensitive preamplifier attached to this electrode. The 1 to 3 T magnetic field from a superconducting solenoid (Fig. 1(a)) is parallel to the axis of the cylindrical, gold-plated-copper electrodes between the photocathode and DEG.

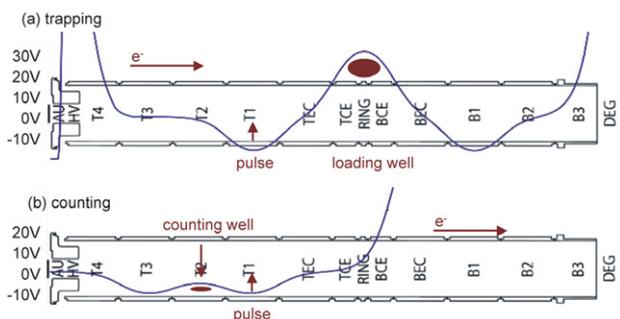


Fig. 2. Cross section of the trap electrodes, with superimposed electric potentials on axis, used for accumulating photoelectrons (a) and for detecting the number of accumulated photoelectrons (b).

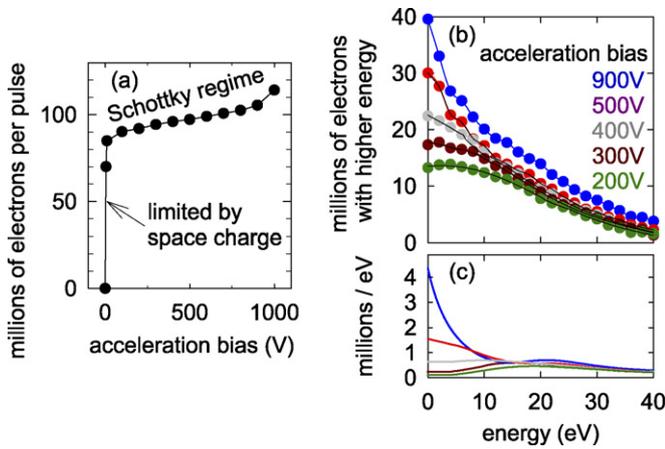


Fig. 3. Room temperature measurements show that the number of photoelectrons per laser pulse increases with the potential applied to the photocathode to accelerate electrons away from it (a). The number of photoelectrons with energies above a blocking potential energy (b), and the derivatives of smooth curves through these data points (c), give an indication of the energy distribution of the photoelectrons.

Fig. 3(a) shows that it is essential to have an electric field at the photocathode to accelerate the photoelectrons away from it, to prevent a space charge buildup that would keep photoelectrons from leaving the cathode. The electrode nearest the photocathode (HV in Fig. 2(b)) is biased so that we operate in the Schottky regime, where the photoelectron yield increases only weakly with increasing electric field, which effectively lowers the work function [2,7]. Although the electrons accelerate as they enter this adjacent electrode they then slow as they leave it.

The axial energy width of the photoelectron pulse is measured using a blocking potential (Fig. 3(b)) applied to one of the electrodes through which the electrons pass as they follow field lines to DEG. An energy width of 20 to 30 eV is observed. The number of low energy photoelectrons, those that are easiest to trap, increases with the electric field at the photocathode (Fig. 3(c)).

Penning traps to capture and accumulate the photoelectrons are formed by biasing the cylindrical trap electrodes located between the photocathode and DEG. The trapping procedure is similar to the method used for trapping antiprotons [12], whereby a suddenly applied voltage completes a potential well around the particles to trap them. As the photoelectron pulse approaches the first of two ~ 10 volt potential barriers (at T1 and B1 in Fig. 2(a)), approximately $1 \mu\text{s}$ after the laser pulse, a rapidly saturated transistor lowers the first of these barrier potentials (T1) by 6 V for about 100 ns. This is long enough for the electrons to enter the region between the barriers, and short enough so that barrier T1 is restored before the electrons reflect off of barrier B1 and escape the trap. For the transistor switch used here, up to a 6-eV slice of the photoelectron distribution is captured.

One nice feature of the photoelectron method is that the captured electrons have only electron volts of energy. Once captured, the electrons cool via synchrotron radiation from their cyclotron motion, with collisions coupling the axial motion of

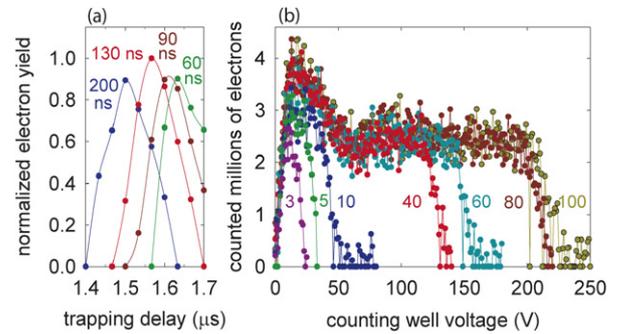


Fig. 4. (a) The number of trapped photoelectrons depends upon pulse duration (inset number) and upon the delay between the laser pulse and the application of the trapping well. (b) The number of electrons that escape as the trap well-depth is reduced in small steps shows that the potential energy distribution of the trapped photoelectrons broadens with increasing numbers of injection pulses (inset numbers).

the electrons along the magnetic field direction to this radiating cyclotron motion. Up to 10 million electrons per laser pulse cool into the smaller central well (RING) between the barriers (Fig. 2(a)) when a cooling time that is roughly the cyclotron damping time is used. More electrons are captured with a longer cooling time, since this allows more axial energy to be collisionally transferred to the damped cyclotron motion. Once the electrons are cooled into the inner well, another injection of photoelectrons can be captured between the two potential barriers.

Accumulated photoelectrons are transferred to T2 (Fig. 2(b)) in preparation for counting their number and measuring their energy distribution. The T1 barrier is then pulsed down by several volts to allow the electrons with the highest potential energies to escape, travel along magnetic field lines, and be counted as they strike the flat DEG, just as described above. The process is repeated after the voltage on T2 is reduced so that more electrons will be released when T1 is next pulsed down.

The number of accumulated charges per laser pulse is shown in Fig. 4(a) as a function of the delay time between the laser pulse and the potential pulse to T1, and as a function of the width of the potential pulse. If the delay is too short, then a longer width gives maximum trapping; if the delay is too long, then a shorter width is advantageous so that the returning electrons do not escape. As the number of laser pulses used to accumulate electrons is increased, Fig. 4(b) shows the increase in the number of accumulated electrons and in the width of the energy distribution. The total number of electrons accumulated into the central well increases linearly with the number of laser pulses (Fig. 5(a)). Despite the good repeatability demonstrated in this example, the number of electrons accumulated depends upon the laser alignment and laser power, both of which can deteriorate slowly with time. To minimize these affects the loading well can be filled with a greater number of electrons than is required, and the trapping well then reduced to a precisely controlled depth to spill out electrons in excess of a well calibrated number. Fig. 5(b) illustrates how the number of laser pulses can then be chosen to accumulate just the desired number of trapped electrons.

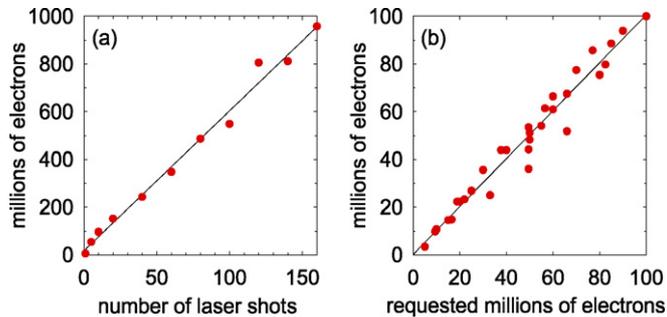


Fig. 5. (a) The number of photoelectrons in a deep trapping well increases linearly with the number of laser pulses. (b) A lower linear accumulation is made very insensitive to slow changes in laser intensity and alignment by lowering and raising the trapping potential to spill injected electrons above a certain number.

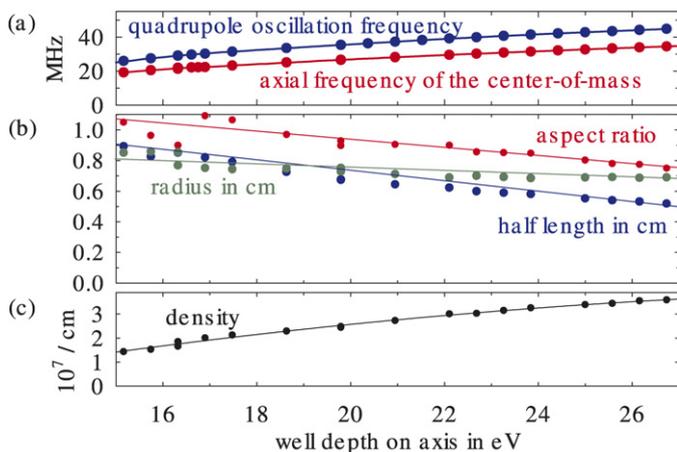


Fig. 6. The oscillation frequencies of the axial oscillation of the plasma center-of-mass and its quadrupole oscillation (a) are measured. These determine the geometry (b) and density (c) of the single component plasma of 35 million electrons, under the assumption that the plasma has a spheroidal shape.

Initial measurements of the oscillation frequencies for the axial motion of the single component plasma's center-of-mass, and of the plasma's quadrupole oscillation frequency have been made (Fig. 6(a)). From these we deduce the geometry (Fig. 6(b)) and the density of the plasma (Fig. 6(c)), under the assumption that the plasma is the spheroidal plasma that one would expect if the trapping potential is a perfect quadrupole potential. Our comparison and full discussion of such plasma diagnostics has been recently reported [26].

The photoelectron loading method is robust enough to work under less ideal conditions than discussed above. For example, we are able to remove the gold photocathode (Au in Fig. 2) and refocus the excimer laser upon the Be degrader that is used to slow antiprotons (DEG in Fig. 2). The applied electric field modifies the ~ 5 -eV Be work function enough so that electrons can be easily liberated by the 5.0-eV photons [2,7]. The loading efficiency is reduced by about a factor of 4, but is still more than high enough to load the large numbers of electrons needed to cool antiprotons. The efficiency reduces a bit more when the excimer laser is sent into the trap vacuum system through an aperture that is only 1 mm in diameter, but is still more than usable.

After this method was realized we learned of a related use of photoelectrons [8]. White light from a slide projector bulb was used to inject long columns of photoelectrons from a Cs_3Sb photocathode into a room-temperature Malmberg trap that had easy access to the light. This approach is not easily compatible with a cryogenic Penning trap needed for antihydrogen production because of the radiant heat from the bulb, the difficulty of delivering the light needed to produce photoelectrons deep within the cold apparatus, and the heat treatment and special handling required to chemically deposit such a photocathode within a trap vacuum. With UV photons from the excimer laser, however, there is enough energy to liberate photoelectrons from simple Au and Be photocathodes which require no special preparation or handling. Also, a short laser pulse naturally deposits negligible heat in the cold apparatus, and the laser light can be focussed through a 1 mm hole more than a meter within a 4 K cryogenic apparatus. The laser is easily steered insofar as metal surfaces struck by the excimer generate detectable photoelectrons. Finally, a much shorter pulse of electrons is generated.

In summary, we report a new, rapid and robust method for the production, loading and trapping of electrons, which can be used for the electron-cooling of antiprotons, or any other application requiring a single-component electron plasma. The photoelectrons produced from incident pulses of UV laser light on a gold thin film provide large numbers of electrons much more quickly than do FEP or thermionic emission loading, and is naturally compatible with producing and trapping the photoelectrons deep within a cryogenic apparatus. The resulting electron plasma is well-centered and well-controlled, and simple metal photocathodes require no special treatment or handling. The number of electrons in the plasma is chosen by selecting the number of laser pulses, and the initial plasma radius is controlled by the illuminated radius of the photocathode. Electrons are loaded close to the trap axis, and the loading time is dramatically reduced, from minutes to seconds. Given the 100 second time between antiproton bunches arriving to be cooled, it is not necessary to miss antiproton pulses to accumulate electrons.

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References

- [1] A. Einstein, *Ann. Phys.* 17 (1905) 132.
- [2] Z. Pei, C.N. Berglund, *J. Vac. Sci. Technol.* 20 (2002) 65.
- [3] Z. Pei, C.N. Berglund, *Jpn. J. Appl. Phys.* 41 (2002) 52.
- [4] X. Jiang, C.N. Berglund, A.E. Bell, W. Mackie, *J. Vac. Sci. Technol. B* 16 (1998) 3374.
- [5] D.A. Orlov, U. Weigel, D. Schwalm, A.S. Terekhov, A. Wolf, *Nucl. Instrum. Methods A* 532 (2004) 418.
- [6] C.K. Sinclair, P.A. Adderley, B.M. Dunham, J.C. Hansknecht, P. Hartmann, M. Poelker, J.S. Price, P.M. Rutt, W.J. Schneider, M. Steigerwald, *Phys. Rev. ST Accel. Beams* 10 (2007) 023501.
- [7] Z.M. Yusof, M.E. Conde, W. Gai, *Phys. Rev. Lett.* 93 (2004) 114801.
- [8] D. Durkin, J. Fajans, *Rev. Sci. Instrum.* 70 (1999) 4539.

- [9] G. Gabrielse, N.S. Bowden, P. Oxley, A. Speck, C.H. Storry, J.N. Tan, M. Wessels, D. Grzonka, W. Oelert, G. Schepers, et al., *Phys. Rev. Lett.* 89 (2002) 213401.
- [10] G. Gabrielse, N.S. Bowden, P. Oxley, A. Speck, C.H. Storry, J.N. Tan, M. Wessels, D. Grzonka, W. Oelert, G. Schepers, et al., *Phys. Rev. Lett.* 89 (2002) 233401.
- [11] M. Amoretti, et al., *Nature* 419 (2002) 456.
- [12] G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R.L. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas, W. Kells, *Phys. Rev. Lett.* 57 (1986) 2504.
- [13] N. Kuroda, H.A. Torii, K.Y. Franzen, Z. Wang, S. Yoneda, M. Inoue, M. Hori, B. Juhász, D. Horváth, H. Higaki, A. Mohri, et al., *Phys. Rev. Lett.* 94 (2005) 023401.
- [14] G. Gabrielse, X. Fei, L.A. Orozco, R.L. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, W. Kells, *Phys. Rev. Lett.* 63 (1989) 1360.
- [15] G. Gabrielse, *Adv. At. Mol. Opt. Phys.* 45 (2001) 1.
- [16] G. Gabrielse, N.S. Bowden, P. Oxley, A. Speck, C.H. Storry, J.N. Tan, M. Wessels, D. Grzonka, W. Oelert, G. Schepers, et al., *Phys. Lett. B* 548 (2002) 140.
- [17] G. Gabrielse, X. Fei, L.A. Orozco, R.L. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, W. Kells, *Phys. Rev. Lett.* 65 (1990) 1317.
- [18] S. Gosavi, J.M. McCarthy, J.L. House, B.G.S. van Mast, G. Janaway, C.N. Berglund, *J. Vac. Sci. Technol.* 19 (2001) 2591.
- [19] C.N. Berglund, W.E. Spicer, *Phys. Rev.* 136 (1964) 1030.
- [20] W. Pong, R. Sumida, G. Moore, *J. Appl. Phys.* 61 (1970) 1869.
- [21] W. Pong, H.K. Nishihara, D. Chan, *J. Opt. Soc. Am.* 62 (1972) 487.
- [22] Y. Matsuura, M. Miyagi, *Opt. Lett.* 23 (1998) 1226.
- [23] Y. Matsuura, M. Miyagi, *Appl. Opt.* 38 (1999) 2458.
- [24] Y. Matsuura, M. Miyagi, *IEEE J. Quantum Electron.* 10 (2004) 1430.
- [25] R.S. Taylor, K.E. Leopold, R.K. Brimacombe, S. Mihailov, *Appl. Opt.* 27 (1988) 3124.
- [26] A. Speck, G. Gabrielse, P. Larochelle, D. Le Sage, B. Levitt, W.S. Kolthammer, R. McConnell, J. Wrubel, D. Grzonka, W. Oelert, et al., *Phys. Lett. B* 650 (2007) 119.