Technological Applications of Trapped Positrons

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Abstract.

Low-energy positron beams are extensively employed in various areas of science and technology such as surface analysis, atomic physics, plasma physics and mass spectrometry. Recent advances in positron trapping and in manipulating nonneutral plasmas present the opportunity for creating a new generation of bright, ultracold positron beams with parameters that far exceed those currently available. Current applications of low-energy positron beams are described, and the potential for the development of advanced trap-based positron beams is discussed.

I INTRODUCTION

Over the past several decades, a variety of powerful analytical tools for materials and surface analysis based on positron beams have been developed [1]. These techniques are generally implemented using steady state and pulsed beams derived from radioactive sources. Recent developments in nonneutral plasma and positron trapping techniques have now created the opportunity for producing a new generation of positron beams based on the extraction of positrons accumulated in a Penning trap. These unique techniques have never before been applied to beam formation, and as described in this paper, they offer the potential to create bright, ultracold, pulsed positron beams with parameters that far exceed current positron beam technology.

This paper is organized as follows. In Sec. II, we describe low-energy positron beams and their current uses for surface analysis and other applications. In Sec. III, we briefly review a high-efficiency positron trapping technique and the formation of positron beams using traps. We also discuss important recent advances in techniques to manipulate nonneutral plasmas and describe how they might be applied to the creation of state-of-the-art cold, bright positron beams. Section IV summarizes the paper.

CP498, *Non-Neutral Plasma Physics III,* edited by John J. Bollinger, et al.

II LOW-ENERGY POSITRON TECHNOLOGY

A Low-energy positron beams

Positrons beams are typically derived from radioactive sources and moderated to low energies using single crystal or polycrystalline metals or insulators [2]. Positron beams are produced from these sources by accelerating, guiding, bunching and focusing the positrons using various combinations of electric and magnetic fields. The resultant low-energy positron beams have been extensively applied to the analysis of solids and surfaces [1], and they have also been employed for several decades in basic atomic physics experiments [3].

B Brightness enhancement and microbeams

For many applications, positron beams with diameters $\sim$ 1 micron or less (microbeams) are required. Such beams can be rastered across a sample under study to obtain spatially-resolved information. When combined with variable energy positron beams that can be implanted to varying depths, a three-dimensional scan of the sample can be obtained. Since radioactive positron sources are typically several mm in diameter, microbeams must be obtained by focusing using electrostatic or magnetic lenses [2].

A fundamental limitation on focusing is imposed by Liouville's theorem, which states that the phase space volume occupied by a swarm of particles moving in a conservative field cannot be reduced. For a particle beam, the phase space volume is represented by the product $\Omega = d^2 \Delta E_\perp$, where d is the beam diameter and $E_\perp$ is the perpendicular energy spread. The minimum diameter d of a focussed beam of initial diameter d_0 accelerated to an energy E is given by $d \approx d_0/\alpha\sqrt{E_\perp/E}$, where α is the convergence angle. For positron beams, typical parameters are $\alpha \sim 0.2$, $E_\perp \sim 0.25$ eV (from tungsten moderators) and $E \sim 2.5$ kV, giving $d \approx d_0/20$. Since $d_0 \sim 3$ mm for typical radioactive sources, the minimum size for a focussed positron beam would be $\sim 150\mu$m, which is too large for many applications.

This limitation has been partially overcome by the technique of remoderation brightness enhancement [4]. Positrons are implanted into a moderator with a well-defined energy. They rapidly thermalize in the moderator and a fraction of them ($\sim$ 30%) are reemitted with a narrow energy spread, which allows them to be further focused in subsequent stages of remoderation. Typically reductions by about a factor of 10–20 in beam diameter are possible. This process is typically repeated 3 or 4 times to obtain microbeams. Unfortunately the 70% loss in each stage results in an overall reduction of about two orders of magnitude in beam strength. As described in Sec. III B, positron traps have the potential for achieving brightness enhancement using much more efficient processes.

C Surface analysis using positron beams

An important application of positron beams is the wide variety of techniques that have been developed for the analysis of solids and surfaces [1]. By varying the energy of the incident positrons over the range from a few kV to >100 kV, positrons can be used for depth profiling.

Positron reemission Microscopy (PRM)—Positrons implanted near the surface of a solid can thermalize and be reemitted and analyzed to yield types of contrast that are not available with conventional scanning electron microscopy. The technique can distinguish non-uniform film thickness, varying crystal orientations, differences in bulk defect density, concentrations of absorbed molecules, and contaminant layers [5].

Positron annihilation induced Auger electron spectroscopy (PAES)—This technique is analogous to electron induced Auger electron spectroscopy (AES), except that the core hole, which leads to the ejection of the Auger electron, is created by positron annihilation rather than electron impact [6]. For this technique, positrons are injected at low energy into the surface to be analyzed. The ejected electrons are analyzed in the usual way, but the measurement is substantially simplified by the absence of background high-energy secondary electrons.

Low-Energy Positron Diffraction (LEPD)—A crystalline sample is bombarded with low-energy (0–300 eV) monoenergetic positrons. Backscattered positrons diffract producing spots on a fluorescent screen. The positions of the spots are a measure of the sample's diffraction sites. This information can be used to determine the crystal structure of a substrate or to analyze adsorbed layers.

Positron Induced Ion Desorption Spectroscopy (PIIDS)—Time-of-flight is used to measure the mass spectrum of ions desorbed from surfaces by the injection of positron pulses [7]. The ion desorption rate due to positron injection is much larger than that for photodesorption.

Positron Annihilation Lifetime Spectroscopy (PALS)—Positrons injected into surfaces can be trapped and subsequently annihilate in vacancy-type defects. Measurement of the positron lifetime yields information about the defects. This technique has been extensively applied to the study of bulk properties of solids [1]. Applications include characterizing the properties of semiconductors, such as ion-implanted silicon to study, for example, stress voiding and electromigration, and voids in polymers, which determine such properties as impact strength, gas permeability and aging characteristics. Another important topic is the development of low-k dielectrics in microelectronic fabrication.

Variable Energy Positron Lifetime Spectroscopy (VEPLS)—The power of the PALS technique can be substantially enhanced using a variable energy beam which enables positrons to be implanted to varying depths so that a depth profile of void size and concentration can be obtained. When implemented using a scanning microbeam, three-dimensional information can be obtained. The technique requires pulse widths of the order of typical annihilation times in materials (~100 ps).

Positron Annihilation Spectroscopy (PAS)—This technique measures the Doppler-broadening of the 511 keV gamma-ray line resulting from the annihilation of positrons implanted into solids. The required information is contained in the gamma-ray lineshape. PAS can provide the same type of information about defects as PALS and VEPLS.

D Positron Ionization Mass Spectrometry

Positron beams have the potential for use in a novel ion source for mass spectrometry. The formation of positive ions by positron annihilation was first demonstrated by Passner *et al.* in a positron trap [8]. The experiment involved introducing sample gases into the trap during positron filling. The positive ions were trapped by the same potentials as the positrons, and mass spectra were obtained using a simple time-of-flight technique. They reported fragmentation patterns for hydrocarbons that were similar to those obtained using electron impact ionization. Subsequently, Hulett and coworkers investigated ionization by positronium formation [9], which occurs for positrons with energies above the positronium formation threshold $E_{Ps} = E_I - 6.8$ eV, where E_I is the ionization energy of the molecule. They found that, for energies slightly above E_{Ps}, very little fragmentation of hydrocarbon molecule occurred, but as the positron energy is increased further, molecular fragmentation increased in a controlled manner.

This effect may be useful in the mass spectroscopic analysis of complex biomolecules of interest in biotechnology and molecular medicine, such as peptides. One possible configuration for implementing this technique using trap-based positron beams consists of a positron trap connected to an ion trap as shown in Fig. 1. By allowing positrons to pass through the ion trap, a recirculating positron beam with well-defined (and potentially very narrow) energy spread can be created in the ion trap. The positron energy in the ion trap can be tuned by varying the depth of the well. Because the beam recirculates, the positrons make multiple passes through the ion trap leading to efficient use of the positrons. Since the ions are confined in a Penning trap, precision mass spectroscopy can be implemented using ion cyclotron resonance.

E Other uses of positron beams

Positron beams are also used for a variety of basic research studies. These include atomic physics [3,10], plasma physics [11], and antihydrogen formation [12]. For many of these applications, the trap-based beams will provide a powerful tool which will provide new capabilities, such as the ability to explore important low-energy regimes and identify narrow-energy resonances that are presently inaccessible to experimental investigation.

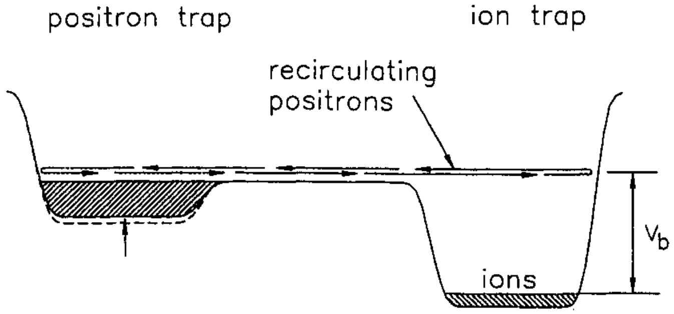

FIGURE 1. Possible configuration for implementing positron ionization mass spectrometry using a trap-based beam.

III POSITRON TRAPS AS BEAM SOURCES

Several research groups have been investigating the use of Penning traps for various aspects of beam formation and handling. Penning traps are currently employed to capture positron pulses from LINACS for pulse-stretching applications [13,14]. The capture and cooling of positrons from a radioactive source using laser-cooled ions in a Penning trap is being investigated for the production of an ultra-cold positron beam [15].

The trap-based beam sources described in this paper employ the high efficiency buffer gas trapping technique that we have developed as described in an accompanying paper in this volume [16]. That paper also describes how the trap can be used as a high quality positron beam source by releasing the positrons in a controlled manner. Beams with energy spreads as low as 18 meV have been created and these beams have recently been applied to the study of positron-atom and positron-molecule interactions in a low-energy regime that is not accessible by any other technique [10].

A unique feature of positron traps is their ability to supply ultra-cold positrons. Once trapped, the positrons cool to the ambient temperature by cyclotron cooling or by collisions. Positrons as cold as 4.5 K have been produced in this way [17] and techniques for producing even colder positrons by collisions with laser-cooled ions are being developed [15]. For the positron beam demonstrated by Gilbert *et al.*, the positrons were cooled to 300 K (0.025 eV) by collisions with room temperature nitrogen at a pressure $\lesssim 1 \times 10^{-6}$ torr The technique could be extended to liquid nitrogen temperatures or even to liquid helium temperatures if hydrogen were used as a buffer gas, because hydrogen is a molecular gas with appreciable vapor pressure at low temperature.

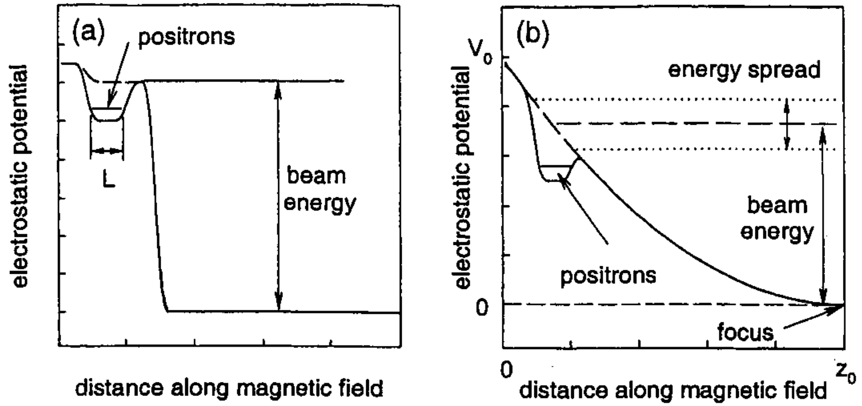

FIGURE 2. Axial potential profiles for creating pulsed beams. (a) Conventional dump and (b) quadratic potential dump.

A Pulsed beam formation using traps

Pulsed positron beams are required for a variety of applications such as VEPLS and time-of-flight PAES. Various techniques have been developed for producing pulsed positron beams in conventional beamlines [1], but these are often complicated and inefficient. Trap-based beams sources have the potential for producing pulsed positron beams in a simple and efficient manner. The simplest technique is illustrated in Fig. 2(a). Positrons are released from the trap by reducing the depth of the potential well in a series of steps. This technique produces pulse widths that are determined by the transit time of positrons in the well. For example, for room temperature positrons in a 1-cm long well, the pulse width would be ~100 ns, which is suitable for many applications.

Pulses of significantly shorter duration are required for VEPELS and TOF-PAES, and these can be produced using the more sophisticated technique shown in Fig. 2(b). The positrons are dumped from the trap by applying a quadratic potential profile to the entire positron flight path, leading to spatial and temporal focusing at the target [2].

To first order, the pulse width is independent of the length of the positron cloud and is given approximately by:

$$\Delta t \simeq 2\left(\frac{m}{e}\right)^{1/2}\frac{z_0 \Delta E^{1/2}}{V_0} \tag{1}$$

where e and m are the charge and mass of the positron, respectively, V_0 is the magnitude of the applied potential, ΔE is the energy spread of the positrons, and z_0 is the length of the length of the buncher. In practice, one might have $V_0 = 500\text{V}$, $z_0 = 0.1$ m and $\Delta E = 0.025$ eV, yielding $\Delta t \sim 150$ ps, which would be suitable

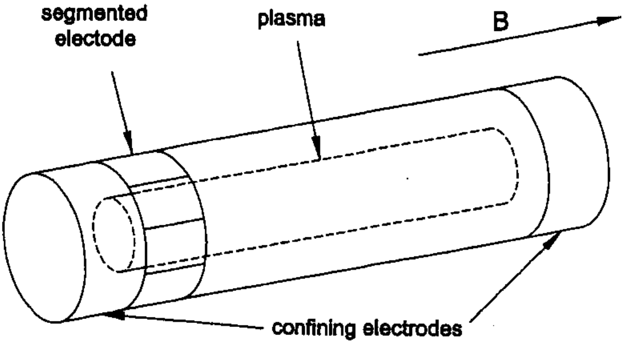

FIGURE 3. Geometry for plasma compression by application of a rotating electric field.

for lifetime spectroscopy. To achieve this performance in a conventional beamline would require multiple stages of rf bunching.

B Brightness enhancement using traps

The capabilities of trap-based beam sources can be further enhanced by the use of recent breakthroughs in trapping technology. The most significant of these is development of a rotating electric field to compress nonneutral plasmas in traps. This has recently been demonstrated by Anderegg *et al.* for an electron plasma [18] and should be equally applicable to positrons. The maximum compression ratio reported was 4.5 in radius, without loss of particles. This would correspond to a brightness enhancement of 20 for a beam extracted from the plasma. Furthermore, it is likely that the technique has not been developed to its limit, so further improvements are possible. In addition, the rotating electric field can be combined with the technique of extracting positrons from the center of the plasma, as described below, to achieve even greater brightness enhancement.

The basic geometry for plasma compression and beam extraction is illustrated in Fig. 3. A cylindrical plasma is contained in a Penning-Malmberg trap. An azimuthally segmented electrode is located near one end of the plasma. A rotating electric field is created by applying suitably phased signals to the ring segments. Plasma compression is observed when the applied frequency coincides with one of the Trivelpiece-Gould modes. Compression is accompanied by plasma heating, so some cooling mechanism must be provided. In the experiments of Anderegg *et al.*, the cooling was provided by cyclotron radiation in the strong magnetic field of a superconducting magnet, which provides a characteristic cooling time $\tau_c(\mathrm{s}) \simeq 4/[B(\mathrm{T})]^2$. For the 4 T field that they used, this gives a cooling time of 0.25 s. For many applications, it would be advantageous to replace the cyclotron cooling with buffer gas cooling and use a low-field conventional magnet to reduce the overall cost of the system.

For nitrogen gas, the cooling rate has been measured at 0.55 s/μTorr [19], so that at a typical operating pressure of 1×10^{-6} torr, the cooling time would be about 0.5 s, which is similar to the cyclotron cooling time of the electron compression experiments. The annihilation time at this pressure is ~30 s. The plasma expansion time at these pressures is ~ 150 s, which is the slowest characteristic timescale in the system. The annihilation time therefore sets the time limit on which plasma compression and extraction must be achieved. Certain other gases are likely to serve as even better cooling agents than nitrogen. For example, for CO, the cooling rate at 10^{-6} torr is ~100 ms, while for CF_4 and SF_6, it is even faster. Since compression rates $\dot{n}/n$ of up to 0.6 s^{-1} were reported by Anderegg *et al.* using large-amplitude drives, it seems likely that significant compression can be achieved using gas cooling.

A second process that can lead to brightness enhancement using traps arises from the nature of the extraction process itself: because there is a radial potential profile within the plasma, particles at the center of the plasma are ejected from the trap before those at the edge. Thus, a beam extracted from a trap is narrower than the plasma, at least for those particles that are ejected initially. The plasma remaining in the trap will then have a hollow profile, which is unstable. The system will come into a stable equilibrium by particle transport. This fundamental property of trap-generated beams, in conjunction with plasma compression, provides a potential method of extending the capabilities for brightness enhancement beyond that obtainable by plasma compression alone.

The narrowest beam diameter, $d_{\min}$, that can be extracted from a plasma of diameter d is determined by the positron space charge, V_s, and the positron temperature T_p, and is roughly given by $d_{\min} \sim d\sqrt{T_p/V_s}$. Typical parameters might be $V_s \sim 10$ V, $T_p = 2$ meV (for cryogenic positrons), yielding $d_{\min} \sim d/70$. If this can be achieved in practice, and combined with a factor of 25 in compression by the rotating electric field, a reduction of more than three orders of magnitude in beam diameter might be achieved in a single stage of brightness enhancement with an efficiency of up to 30%. Furthermore, these results can be achieved using high-efficiency neon moderators, which have too large an energy spread to be used in conventional remoderation brightness enhancement systems. Even if the actual performance is an order of magnitude below this value, the system would still represent the state-of-the-art in positron beams. Furthermore, the analysis presented above ignores the electrostatic focusing that could potentially produce an additional factor of 10 if the positrons are extracted from the magnetic field.

C Proposed Developments

First Point Scientific, Inc. (FPSI) is currently addressing the issue of trap-based beams by developing an advanced positron beam source (APBS) based on the accumulation of positrons from a radioactive source in a Penning trap [20]. The

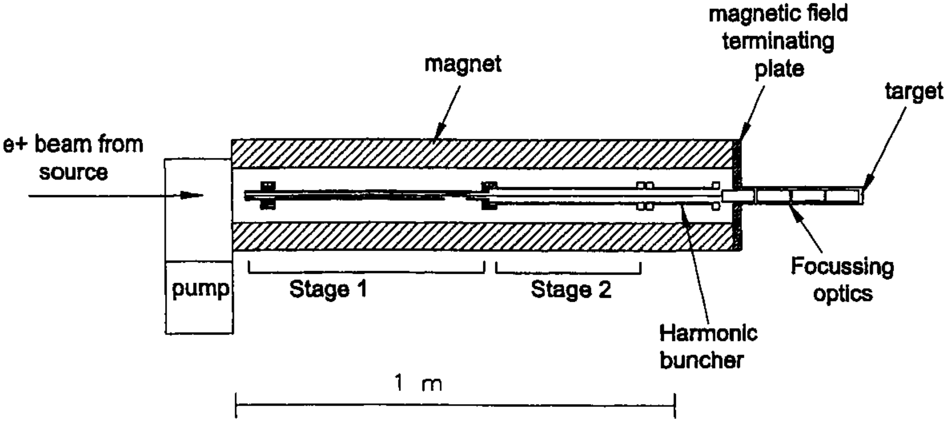

FIGURE 4. Layout of and the APBS showing the two stage trap, quadratic potential buncher, and electrostatic extraction optics.

new source uses the trap to create short positron pulses, followed by extraction from the magnetic field into an electrostatic beam line (Fig. 4). The APBS will include the following features:

- Simplified low-cost, two-stage, design.
- Integral quadratic potential buncher capable of producing subnanosecond positron pulses.
- Electrostatic optics for extracting the beam from the magnetic field.

FPSI is also considering the development of a complementary system in the form of a positron trap beam source (PTBS) that will employ a conventional three-stage design. While the PTBS will not be as economical as the APBS, it will include the following additional advanced features:

- Rotating electric field for plasma compression permitting high efficiency brightness enhancement.
- Controlled extraction of the positrons from the center of the plasma to further increase the brightness enhancement.
- Cryogenic electrodes to produce ultra-cold positrons.

These two systems have the capability of providing state-of-the-art postron beams for a variety of technological applications such as those described in Sec. II C.

IV SUMMARY

Current developments in the fields of nonneutral plasma science and positron trapping technology have introduced exciting opportunities for the creation of a new generation of positron beams in the form of trap-based beam sources. These novel beam sources are based on new techniques that have never before been applied to beam production. They offer the possibility of producing state-of-the art positron beams with performance parameters more than an order of magnitude better than current systems. When incorporated into surface analysis tools used by industry and research, they offer the potential for substantially improved performance at lower cost. For scientific users, they offer new capabilities and the potential to investigate regimes not presently accessible to experiments.

ACKNOWLEDGMENTS

The work at FPSI is supported by the National Science Foundation under SBIR Phase I award number 9861217. At UCSD, the continued development of positron trapping technology is supported by the Office of Naval Research and the research in positron atomic physics by National Science Foundation.

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