A Scheme to Produce a Dense Positronium Plasma for an Antihydrogen Experiment

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Abstract.

A 6 MeV industrial electron linac with 0.2 mA average current will be installed in December 2007 in CEA-Saclay. Equipped with a tungsten target and moderator, it is aimed at producing rates of order 10^8 s^{-1} slow positrons. This setup is part of a project to demonstrate the feasibility of an experiment to produce the H^+ ion for a free fall measurement of H. The energy is below the neutron activation threshold. Its small size and cost could be of interest for a university laboratory or industry, and could be envisaged as a replacement source for the antihydrogen experiments at CERN.

Keywords: Positron beam, Antihydrogen, Positronium.
PACS: 04.80.Cc, 07.77.Ka, 29.25.-t, 41.75.Fr

Presented at the 11th International Workshop on Slow Positron Beam Techniques for Solids and Surfaces (SLOPOS-11), 9-13 July 2007, Orléans, France

Submitted for publication in Applied Surface Science

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INTRODUCTION

Our motivation is to demonstrate the possibility to use a small electron linac as a source of slow positrons for an experiment to produce antihydrogen and measure its free fall. This compact apparatus could also be used for materials science applications.

ANTIHYDROGEN EXPERIMENT

The possibility that antimatter may behave differently from matter in the earth's gravity field is a long-standing issue. Extended supergravity theories were indeed found to potentially contain gravivector fields that would lead to an antigravity component [1]. Although indirect experimental constraints lead to severe limits on such forces [2], it is worthwhile to perform a direct measurement.

The antihydrogen atoms currently produced at CERN [3] are obtained mainly via a three-body interaction of an antiproton in a dense cloud of positrons. This process creates highly excited atoms emitted isotropically at high velocities, thus with characteristics not adequate for a free fall measurement. Walz and Hänsch proposed to use instead the H^+ ion in order to collect ultracold atoms [4]. We proposed a way to prepare such ions using interactions of the antiprotons with a dense target of positronium atoms (Ps) [5, 6]. In such a scheme, it is necessary to dispose of a large quantity of positrons as the density of Ps atoms required is of the order of 10^{13} cm^{-3} in order to obtain one ion [7] to ten [8] ions when a bunch of 10^7 antiprotons passes through this target.

Simplified Scheme

We have now preliminary experimental results that enable to simplify the scheme described in a previous publication [5]. First a linac based electron beam interacts with a tungsten target to produce a high rate of positrons at peak energy around 1 MeV. These are slowed down using preferably a solid gas moderator and stored in a Penning-Malmberg trap up to a number of several 10^{10} in typically 100 seconds.

We have performed a test with the RIKEN trap which shows that we can directly extract a 75 ns FWHM wide pulse containing 1.3 10^{10} positrons [9]. Further bunch compression is possible as shown for instance at lower intensity by Cassidy et al. [10]. The beam diameter can be kept around 1 mm after extraction from such a trap when using the rotating wall technique. Such a fast extraction is necessary because of the 142 ns lifetime of oPs that is subsequently formed.

The extracted positrons can then be dumped onto a material that will convert them into Ps. The density of this Ps cloud may be maintained with the use of reflector walls, making a cavity of dimensions ~ 1 cm x 1 mm^2. We are currently studying how to obtain films of SiO_2 that have a high e^+ to slow Ps conversion efficiency, and reemit a large fraction of the produced Ps atoms into vacuum. Using slow positron beams equipped with a time of flight detector at AIST (Tsukuba) [11] and at CERN [12], we have results of 36 % conversion efficiency into oPs and average reemission energy lower than 100 meV [13]. This low value improves over the usual 2-3 eV work function emission from metals as the density of the Ps target cloud is inversely proportional to its velocity. Gidley et al. claim that Ps may even be thermalized in the material before emission into vacuum [14]. Our apparatus at CERN includes a sample holder that can be cooled down to 10K in order to study this possibility.

The Ps cloud may also be illuminated by a laser system to excite these atoms in order to benefit from the increase in the p + Ps → H cross-section, expected to be proportional to the main quantum number to the fourth power. A large fraction of the antiproton bunch would then be converted into excited antihydrogen atoms. Part of the H atoms may further interact with other Ps atoms to produce H^+.

The antiproton beam should be collimated in order to match the transverse dimensions of the cavity holding the Ps cloud, and delivered in a short bunch at energies, depending on the excitation state of the Ps atoms, up to 10 KeV. We believe the best way to achieve these goals is to store the antiprotons in a trap such as the one developed in the ASACUSA collaboration [15].

SLOW POSITRON PRODUCTION

In [6] we proposed the idea to use a 10 MeV / 2 mA electron accelerator in order to achieve the high positron rates needed. The low energy induces low positron production rates that can be overcome with a high average current. Recently we have had the opportunity to purchase a small industrial linac from Linac Technologies [16]. Its nominal energy and average current are 6 MeV and 0.2 mA. The repetition rate is 300 Hz with bunch length adjustable between 1 to 4 µs. The magnetron peak power is 2.6 MW. The total power consumption is 10 kW. The acceleration length is 21 cm after which the beam diameter is 1 mm. The overall dimensions are roughly 1 m x 0.5 m x 0.5 m. The low energy and current, compared to our initial aim, are due to financial issues. However, the average positron energy is lowered to 800 keV, which is advantageous concerning moderation efficiency.

Simulations, performed with the GEANT3 software [17], predict rates of 5 10^{11} e^+ s^{-1} when the beam hits a 200 µm thick target at 5 degree incidence angle (Figure 1). At such low incident energies the positrons are emitted almost isotropically from the target, with 2/5 of these positrons emitted backwards from the incident beam direction.

A tungsten moderator of 10^{-4} efficiency would thus produce 3 10^7 slow e^+ s^{-1}. We have foreseen to install a set of transport coils and a dipole in order to separate the electrons from the positrons, thus opening the possibility to use a solid gas moderator with at least 10 times higher efficiency after including transport losses due to the large beam size.

The overall dimensions of this project (Figure 2), including the concrete shielding against X rays, is 6 m x 4 m x 3 m, making it a compact setup compared to higher energy accelerators or nuclear reactors.

Such a source may be adapted to the needs of materials science research by transforming the pulse time structure for instance with a trap and additional buncher such as developed by R. Suzuki et al. [18] at AIST (Tsukuba) who were able to obtain sub ns bunches each with few positrons, a variable bunch spacing and a high repetition rate.

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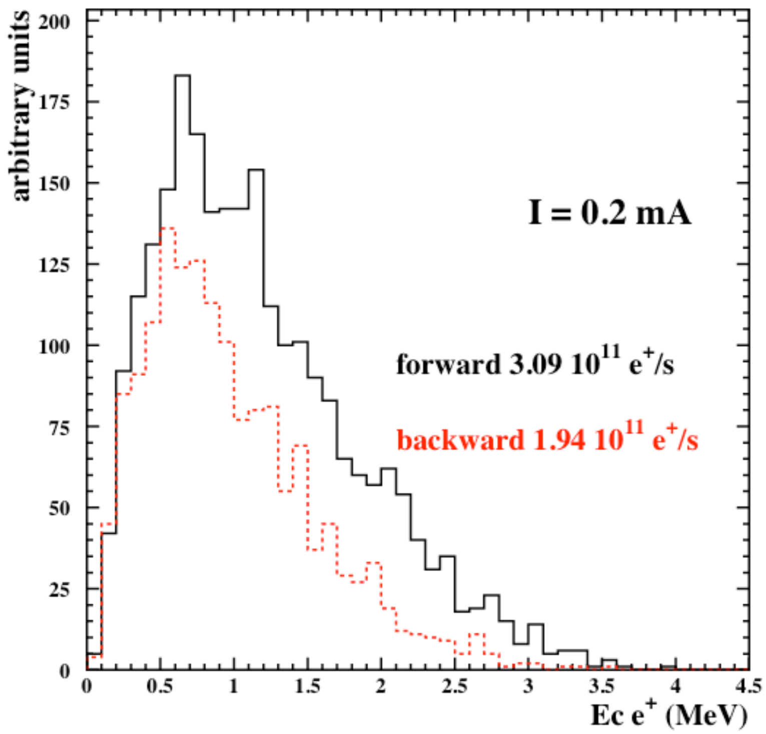

Figure 1 Kinetic energy spectrum of the produced positrons in 100 keV bins, for 6 MeV electron energy. The integral forward and backward emitted rates are shown.

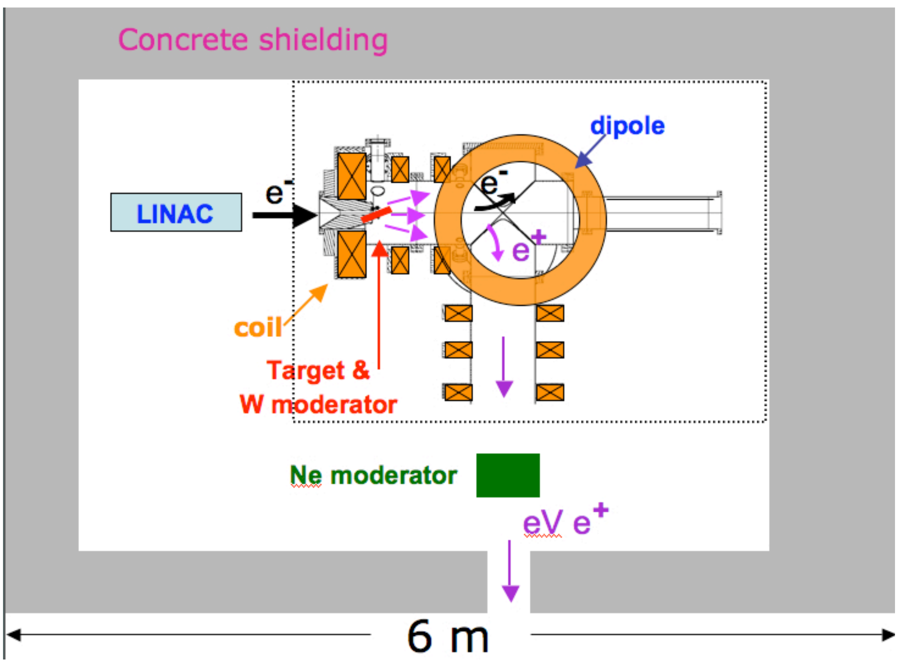

Figure 2 Schematic layout of the planned positron source.