A HIGH INTENSITY POSITRON SOURCE AT SACLAY: THE SOPHI PROJECT

O. Delferrière, P. Pérez, J.M. Rey, L. Liszkay, A. Curtoni, M. Carty, Y. Sauce, V. Blideanu,
N. Ruiz, CEA-Saclay, DSM/IRFU, 91191 Gif-sur-Yvette, France
J.L. Lancelot, D. Neuvéglise, F. Forest, SIGMAPHI Zi Du Prat Rue Des Frères Montgolfier,
Vannes, Morbihan 56000, France

Abstract

One of the fundamental questions of todays physics concerns the action of gravity upon antimatter. No experimental direct measurement has ever been successfully performed with antimatter particles. An R&D program has been launched at IRFU (CEA/Saclay) to demonstrate the feasibility of the production of antihydrogen (H) with the use of a target of positronium (Ps) atoms (the bound state of an electron and a positron). This target, when bombarded with antiprotons, should allow combining its positrons with the incoming antiprotons and create H atoms and H^+ ions. This experiment needs a large amount of Ps atoms, thus an intense source of positrons is necessary.

We are building the SOPHI experiment in Saclay, which is a device based on a small 5.5 MeV electron linac (1) to produce positrons via pair production on a tungsten target. This device should provide 10^8 slow e^+/s, i.e. a factor 300 greater than the strongest activity Na^{22} based setups. A Penning-Malmberg trap can be adapted to store and extract 10^{10} to 10^{11} positrons in ultra high vacuum conditions.

The SOPHI system has been finalized at the end of 2006 and the main components have been studied and built during 2007(2). The experiment is currently assembled and first results are expected in June 2008.

The Linac, beam production and transport system will be described and the project status reported.

INTRODUCTION

A difference between the free fall of matter and antimatter would signal a violation of the Weak Equivalence Principle. There are indirect limits on its validity with antimatter. However they are model dependent or controversial. Projects to detect the free fall of charged antiparticles, in the gravity field of the Earth, all failed because of the difficulty to shield the apparatus against electromagnetic forces 0. We propose a direct measurement with antihydrogen atoms, H, by first producing the antihydrogen ion H^+ 0, as suggested by J. Walz and T. Hänsch 0. This ion can, in principle, be cooled down to 20 µK, by sympathetic cooling with ordinary laser-cooled ions. Velocities less than 1 m/s could be reached for a quasi-vertical free fall. After photo detachment of the extra positron to recover the neutral atom, a simple time of flight measurement then becomes straightforward with almost negligible errors compared to the dominant one, which comes from the effectively attained H^+ temperature. In order to produce these H^+ ions, we propose to use the set of two reactions: $p + Ps \rightarrow H + e^-$, followed by $H + Ps \rightarrow H^+ + e^-$, from interactions of antiprotons and H with the same positronium target. Using measured cross-sections as well as calculated ones, if 10^7 antiprotons interact with a density of 10^{12} cm^{-3} Ps atoms, 1 H^+ ion is produced, together with 10^4 H atoms 0. In the route towards this measurement, several challenges must be overcome. The first will be to produce 10^8 slow e^+/s using a small linac and a solid Neon moderator.

TOWARDS A HIGH INTENSITY POSITRON BEAM

The project to measure the gravitational acceleration of antihydrogen atoms requires the production of a dense target of positronium atoms, the e^+e^- bound state with a lifetime in the triplet state of 142 ns. A large amount of "slow" positrons (energy range from eV to a few keV) is necessary. Radioactive sources based on Na_{22} are not intense enough. Moreover, the efficiency of the moderation process, which allows slowing down the positrons, must be taken into account. It varies from 10^{-5} to 10^{-2} according to the moderator type which can be used in the experimental environment and the incoming positron beam energy. The possibility to produce positrons of low energy with an accelerator has thus been studied 0. The process employed is pair creation from an electron beam hitting a target of high Z. For such an experiment, a dedicated beam is necessary. The price of accelerators led us to study the performances of an accelerator of very low energy (<10 MeV) compensating the low cross section by increasing the intensity of electron beam, this being limited by how the target sustains heating for an intensity of order of 1 mA. This study resulted in a patent 0.

Our project, named SOPHI, consists in building a selector between electrons from the primary beam and the positrons emitted by a tungsten target at low incidence angle 0. This selection opens the possibility to use a moderator with solid Neon to slow down efficiently the

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positrons from MeV to eV energies, rather than a tungsten moderator roughly 100 times less efficient. Indeed, the temperature of solid Neon at 7K does not allow placing this type of moderator in the direct environment of the electron beam which has a power of order of kW.

THE SOPHI PROJECT

One of the major problems in the positron production using electron impact on a W target is the very high energy spread in addition to a very wide distribution angle (Fig. 1). The average exit angle with respect to the beam is large, of the order of 50 degrees and even larger for the lowest positron energies. Previous studies have been performed to design a positron collector able to transport them efficiently up to the Penning trap entrance. In this scheme, in order to take advantage of this wide angle of production, a system of coils producing diverging magnetic field lines at the location of the target was used. The divergent magnetic lines were created by a superconducting coil and collected by a large diameter coil to form a magnetic bulb 0. In 2006 a new scheme has been foreseen, based on classical low magnetic field solenoids, providing both the collection of positrons, the transport and e^+/e^- separation (Fig 2).

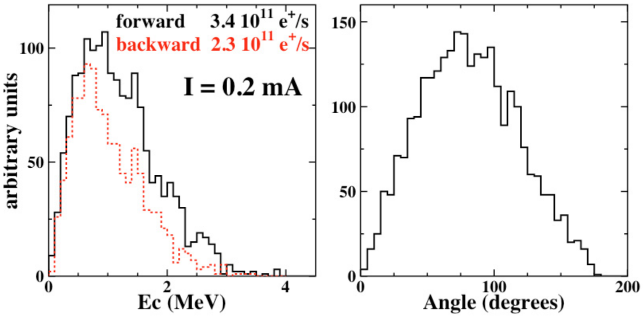

Figure 1: Spectra of the kinetic energy and production angle of positrons for electrons with 5 degree incidence angle on target at a beam energy of 5.5 MeV.

EXPERIMENTAL SETUP

In 0 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. Its nominal kinetic energy and average current are 5.5 MeV and 0.2 mA. The repetition rate is 200 Hz with bunch length adjustable between 1 to 4 µs. The magnetron peak power is 1.9 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 1 m x 0.8 m. The average positron energy is then lowered to 800 keV, which is advantageous concerning moderation efficiency. Simulations, performed with the GEANT3 software 0, predict rates of 5.10^{11} e^+ s^{-1} when the beam hits a 200 µm thick target at 5 degree incidence angle. 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}.

Once emitted from the tungsten target the positrons are collected by a magnetic setup. This setup consists in seven solenoids ensuring successively the capture of positrons then there extraction from the residual electron beam and finally the guidance to the moderator, or in a first step to the detector to measure the positron production efficiency. Due to the large transverse size of the positron beam the vacuum vessel has been realized with a 300 mm inner bore the solenoids being even bigger with a 340 mm inner diameter. The current in all the solenoids can be individually adjusted to allow an optimum collection and transmission efficiency to be found during the commissioning of the positron source. The coils are not shielded and the maximum magnetic field is about 0.28 T. A magnetic shielding has been fixed on the linac support, to minimize the magnetic field in the cathode region (now ~0.5 10^{-4}T) and eliminate the field effect on the electrons at low energy. As the system is not axisymmetric, the remaining stray field level between the shielding hole and the W target induces a beam deflection of about respectively 1.5 mm and 2 mm in the vertical and horizontal direction, that can be corrected by moving the target position.

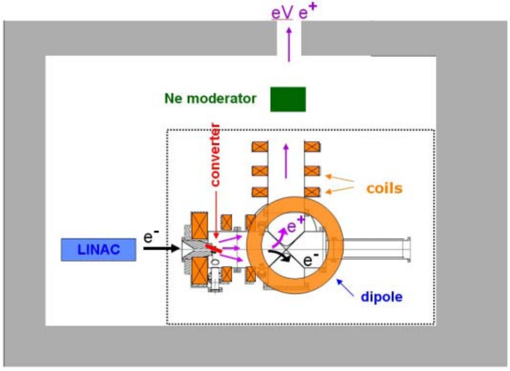

Figure 2: SOPHI magnetic configuration for e^+ and e^- transport and separation using TOSCA

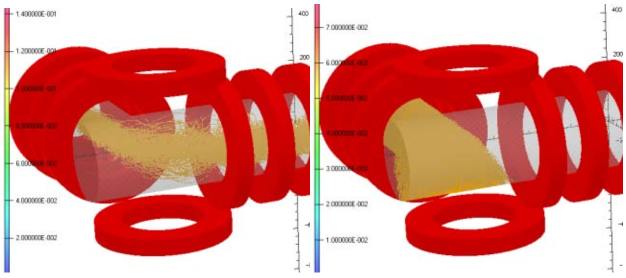

Figure 3: TOSCA trajectories simulation of positrons (left), and electrons (right)

Transport simulations (Fig. 3) have been performed using the 3D TOSCA code 0. The magnetic field gradient generated by the first two coils on either side of the converter allows the positrons capture. The capture efficiency is of the order of 80%, the other part of the positrons is going backward. The currents in the dipole coils and transport coils are then adjusted to eliminate all the electrons, as the positrons turn in the opposite direction and are guided towards the moderator.

STATUS OF THE PROJECT

The set comprising the target holder, the vacuum vessel and the coils for the e^+/e^- selector, has been built by the French company SigmaPhi (Fig. 4) and assembled in IRFU at Saclay. The concrete shielding is installed in our laboratory at Saclay, including the electric power supplies and water-cooling system. The linac is currently under test at Linac Technologies Company for current, beam profile, and energy measurements. Long test runs of 8 hours are foreseen for reliability characterization. The next step is the delivery at Saclay, where a new set of verifications will be made for final acceptance.

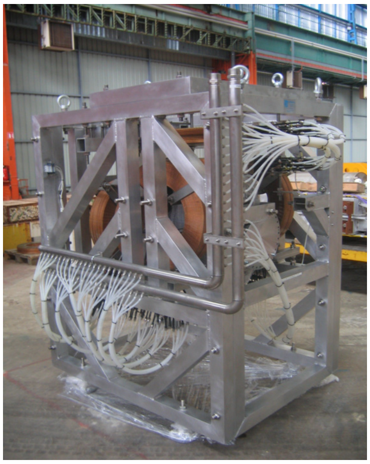

Figure 4: SOPHI magnetic system built by ΣΦ

The full assembly of SELMA and SOPHI (Fig. 5) in the cavern is expected for the end of June. The first positron measurements with the linac (Fig.6) will be performed in July 2008 with an array of Faraday cups to determine the e+ beam profile and current. This detector will be later replaced by a more elaborate one to measure the energy spectrum at the same time.

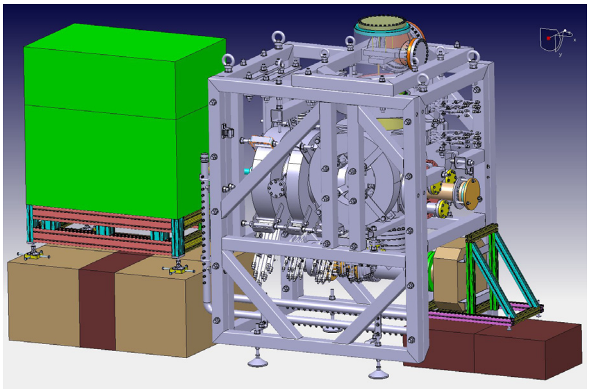

Figure 5: Realistic view of the magnetically shielded linac (green) connected to the SOPHI magnetic system

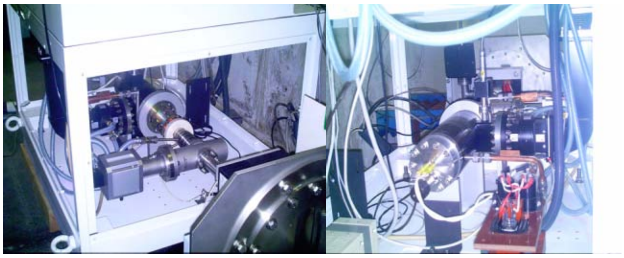

Figure 6: SELMA Linac without shielding built by *Linac Technologies*

EXPECTED IMPROVEMENTS AND APPLICATIONS

Further work is currently under way to study a coupled electric and magnetic system for positron beam size reduction after moderation, allowing the injection and storage into a Penning-Malmberg trap, for which a small aperture in necessary to avoid heating of the cold structure of the superconducting solenoid.

The overall dimensions of this project, 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. 0 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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