A High Intensity Positron Source at Saclay: the SOPHI Project

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Abstract. We are building the SOPHI experiment in Saclay, which is a device based on a small 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 setup. 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 being assembled and first results are expected for autumn 2008. The electron linac, positron beam production and transport system will be presented, and expected positron production rate reported.

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INTRODUCTION

One of the fundamental questions of today's physics concerns the action of gravity upon antimatter. 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 [1]. 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 [2]. No experimental direct measurement has ever been successfully performed with antimatter particles. We propose a direct measurement with antihydrogen atoms, H, by first producing the antihydrogen ion H+ [3], as suggested by J. Walz and T. Hänsch [4]. 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. An R&D program has been launched at IRFU (CEA/Saclay) to demonstrate the feasibility of the production of antihydrogen 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 anti H atoms and H+ ions.

In the route towards this measurement, several challenges must be overcome. As this experiment needs a large amount of Ps atoms, an intense source of positrons is necessary. The first challenge will be to produce 108 slow e+/s using a small linac.

AIM OF THE SOPHI PROJECT

The possibility to produce positrons of low energy with an accelerator has thus been studied [5]. In order to reach a compromise of positron cross section and positron bunches with a low angular dispersion; the suggested ideal accelerator is an ~30 MeV electron linac. As the losses in the positron cooling process after such a system are very high (10-5 to 10-3 efficiency) we came to the conclusion that, despite a lower cross section, electrons of less than 10 MeV would be better adapted to generate positrons of relatively low energy, and to compensate the low cross section by increasing the intensity of the electron beam. This study resulted in a patent [6]. 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 angular distribution (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.

Our project, named SOPHI (French acronym for Source of Positrons of High Intensity), consists of building a prototype of this patented solution. This apparatus opens the possibility to use a moderator with solid Neon to slow down the positrons from MeV to eV energies effectively, rather than a tungsten moderator roughly 100 times less efficient than the solid Neon moderator. Indeed, the temperature of solid Neon at 7 K does not allow placing this type of moderator in the direct environment of the electron beam, which has a power of order of kW.

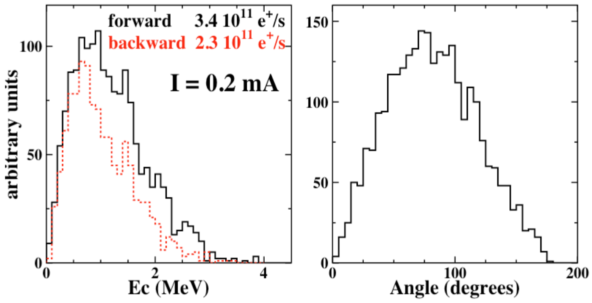

FIGURE 1. Positron production: spectra of the kinetic energy and production angle of positrons downstream of the target for 107 electrons. On the right: view of the positron emission from the target without magnetic field. (GEANT3 simulations).

Previous studies have been performed to optimise a positron collector able to transport them efficiently up to the moderator entrance. During the year 2006 a final scheme has been designed then built in 2007 and 2008, based on resistive low magnetic field solenoids, providing both the collection and transport of positrons, and e+/e- separation (Fig 2).

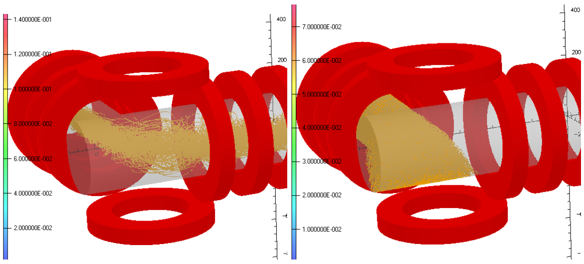

FIGURE 2. Collection and transport of positrons on the left, and e+/e- separation on the right. (3D TOSCA transport simulation).

THE 5 MEV LINAC

In [5] 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 purchased a small industrial linac from Linac Technologies [7]. Its nominal kinetic energy and average current are 5.5 MeV and 0.2 mA (Fig 3). The repetition rate is 200 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 1 m x 0.8 m.

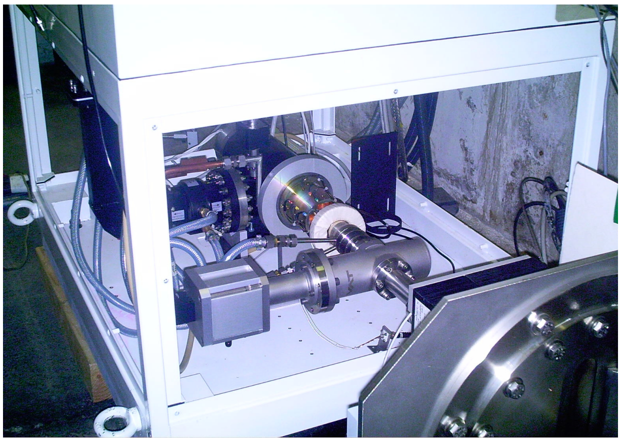

FIGURE 3. View of the linac

POSITRON PRODUCTION

The average positron energy emitted from the W target has a mean value of 800 keV and ranges from 0 to 3 MeV, which is advantageous concerning moderation efficiency, compared to a higher linac energy. Based on the 0.2 mA beam of 5.5 MeV energy simulations, performed with the GEANT3 software [8], predict rates of 5.1011 e+ s-1 when the beam hits a 200 µm thick target at 5 degree incidence angle. This small angle provides greater heat transfer and positron emission in vacuum while keeping an effective target thickness for the incoming electrons [5].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 3 107 slow e+ s-1.

THE MAGNETIC COLLECTOR

Once emitted from the tungsten target the positrons are collected by a magnetic setup. This setup consists of seven solenoids ensuring successively the capture of positrons, their extraction from the residual electron beam and finally the transport 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 10-4T) 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 1.5 mm and 2 mm in the vertical and horizontal direction respectively, that can be corrected by moving the target position.

Transport simulations have been performed using the 3D TOSCA code [9]. The magnetic field gradient generated by the first two coils on either side of the converter allows the positron 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. This means that local field configuration can be finely tuned to recover 50% of the positrons emitted backward (in the linac direction). Space has been kept at the entrance part of the system to optimize the magnetic field configuration using steel parts.

RADIOLOGICAL PROTECTION

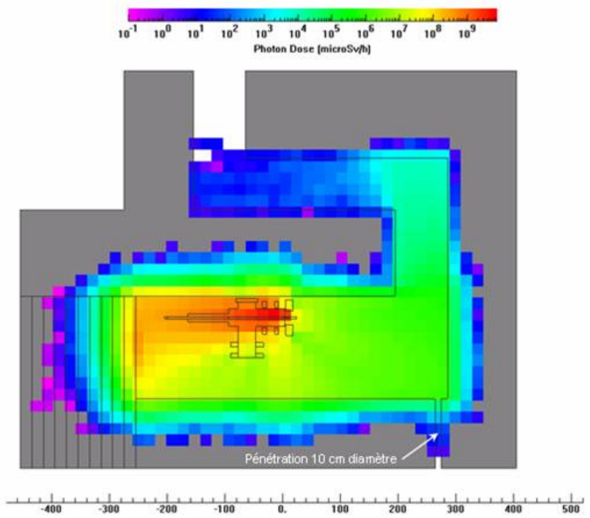

FIGURE 4. Radiological protections in normal operating condition

Among the advantages of using a linac producing electrons of less than 10 MeV is the radiological protection (Fig. 4) that can be used around the apparatus. As neutron activation does not occur below 10 MeV steel reinforced concrete can be used as radiological shielding thus providing magnetic shielding as well. One of the major safety issue concerns the venting and Ozone evacuation from the inside of the concrete shielding.

FIGURE 5. The vacuum vessel and the coils for the e+/e- selector built by SigmaPhi

STATUS OF THE PROJECT

FIGURE 6. The concrete shielding installed in our laboratory.

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. 5) 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 (Fig. 6). 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. The full assembly of SOPHI (Fig. 7) in the cavern is expected for the end of June. The first positron measurements with the linac will be performed in autumn 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. The production of 3x1011 positrons ranging from 100 keV to 3 MeV is expected at full power of the linac.

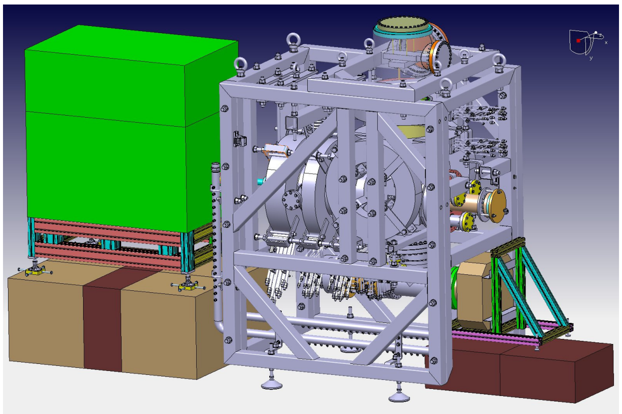

FIGURE 7 Full assembly of SOPHI, the green part is the linac with its magnetic shielding.

FUTURE DEVELOPMENTS

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 is 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. [10] 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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