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Development of a Positron Generator Dedicated to Materials Science Applications

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Abstract

Positron beams are getting increasing interest for materials science and for fundamental research. Recent progress on positron production using a compact electron accelerator made at CEA-IRFU for the GBAR experiment is providing new prospect for material analysis and non-destructive testing technology using positrons. CNRS-CEMHTI is defining a long term strategy to boost its positron laboratory using an upgraded version of the CEA positron generator manufactured by the POSITHÔT company. This new generator is designed to produce between 2 and 3 x 10^7 slow positrons per second to feed in parallel several experiments. It will be presented here as well as the future beam developments.

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1. The growing interest in positrons

1.1. Positrons for fundamental physics

Several projects are underway that will make extensive use of positrons. The already established experiments at CERN that produce antihydrogen atoms, i.e an antiproton bound with a positron, will perform spectroscopy of

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atomic levels on these anti atoms in order to compare with those of hydrogen (ALPHA Amole (2014)), ASACUSA (1997) and ATRAP (Gabrielse (2001)) aiming to test the CPT theorem with antimatter. Other experiments also being prepared at CERN aim to compare their behavior under gravity. AEGIS (Doser (2012)) and GBAR (2011) (see section 3.1) will combine antiprotons with positronium, which is a bound electron-positron pair, to produce antihydrogen. Cassidy (2014) at UCL wants to measure the free fall of positronium, and Crivelli (2014) at ETHZ prepares for a high precision spectroscopy of positronium. All such experiments need positrons. Some are happy with the flux produced from ^{22}Na sources while the more challenging ones need more.

1.2. Positrons for materials science

Positrons are also used in materials science to probe point defect concentration (Tuomisto (2013)). Compared to physics research experiments, beams of positrons used for material sciences imply the use of a moderating stage to make low energy quasi monoenergetic beams. Several techniques coexist under the name “positron annihilation spectroscopy” having in common measurement of the 511 keV gamma. Gamma analysis is made either as a function of energy using the Doppler shift or as a function of time using a “life time” concept.

The positron annihilation spectroscopy is acknowledged as the most efficient way to characterize point defects and aggregates of defects within materials in a non-destructive manner. It has been identified by the ITRS (International Technical Roadmap for Semiconductor 2013) as an enabling technology for the development of the next generation of semiconductors (Krause-Rehberg 1999).

1.3. Positrons production

Most of the positron beams used for materials science applications are obtained using radioactive ^{22}Na sources. These sources produce positrons with peak energy of 540 keV before moderation (Brandt 1974). The positron production rate of a 50 mCurie sources when new is 1×10^5 slow positrons per second with a conventional tungsten moderator and can go up to 5×10^6 slow positrons per second with a finely designed cryogenic moderator using condensed neon gas in its solid state (operated at 7K). Higher positrons fluxes are obtained in research facilities, either on research reactors or on accelerator facilities. The highest positron flux of 10^9 slow e^+/s is produced on the FRM II (Hugenschmidt 2008) research reactor in Garching (Germany). The Delft reactor is also equipped with a positron extraction line (van Veen (1997)) while the MacMaster University in Ontario (Canada) (MacMaster 2014) and the Kyoto University (Japan) (Sato 2015) are currently modifying their research reactors to have extraction line dedicated to positrons production. Accelerators facilities having long experience in positron production are in Tsukuba (Japan) (Oshima 2009) and Rossendorf (Germany) (Krause Rehberg 2008). The optimum production rate using accelerator occurs for incident electrons having more than 10 MeV energy thus creating neutrons and radiological activation. All the common ways to produce positrons suffer a major drawback: they generate radioactive wastes.

To eliminate all the drawbacks of the previously cited ways to produce positrons a new production scheme using a low energy electron linac has been developed by CEA-Irfu and will be described in the next paragraphs.

2. The cost of positrons

A major limiting aspect for the use of positrons is their cost. Using a 50 mCi ^{22}Na positron source (the most powerful positron source available) usually means investing 40 k€ every 6 years (twice the half-life period of 2.6 years).

Assuming a flow of 10^5 slow positrons per second (typical number obtained with a tungsten moderator) with 6 years of use, the specific cost of positrons comes to 5.3 € per 10^9 slow e^+/sec. A cryogenic neon moderator reduces this cost despite a far higher investment cost (around 0.5 M\$), but the wider energy distribution of the positron moderated by neon (3 eV instead of 0.3 eV for polycrystalline tungsten (Ley 1997)) generates a larger beam, less convenient to handle for materials science analysis.

Estimating the cost of positrons coming out of a research reactor is more difficult as the real cost of safety and manpower is hard to obtain. It also has less sense for comparison as building a research reactor dedicated for positron production is not an option for most scientific and industrial applications.

The compact linac based positron generator issued from the developments presented in the next paragraph, and in the process of being commercialized by the POSITHÔT company, will provide positrons at a specific cost twice lower than radioactive ^{22}Na sources (estimation for a use integrated over a 6 years period with a 90% working time yearly).

3. The compact positron generator developed for the GBAR experiment at Saclay

3.1. General scheme of the GBAR experiment

In order to perform a free fall experiment proposed by the GBAR collaboration following Walz and Hänsch (2004) scheme, the anti-atoms must be very cold. Velocities of the order of 1 m/s correspond to tens of μK or a few neV. It is not possible to reach such low velocities using directly the neutral anti hydrogen atom. In 2004, Walz and Hänsch proposed to use an intermediate ion, the anti H^-, denoted here $\bar{H}^+$, because it can be cooled to such low temperatures using laser techniques (Roth 2005). The scheme is thus to first produce this anti-ion, and then photo detach the extra positron with a laser to obtain an ultra-slow neutral anti-atom. This anti-atom falls under gravity onto a plate where it annihilates, producing several pions that are easily detectable. The distance between the laser beam and the annihilation plate defines the height of the free fall, whereas the free fall time is that between the laser shot and the detection of the pions. The GBAR production scheme of the anti-ion is obtained from the two step charge exchange process: $\bar{p} + Ps \rightarrow \bar{H} + e^-$, followed by $\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$, from interactions of $\bar{p}$ and $\bar{H}$ with the same positronium target. The 5 MeV antiprotons from the Antiproton Decelerator at CERN are further decelerated to 100 keV energy in the ELENA ring and even more in GBAR with a drift tube down to 1 keV, and focused onto the positronium target. An electron accelerator produces positrons by interaction of the electrons with a tungsten target. These MeV positrons are themselves decelerated to a few eV with a moderator made either of tungsten meshes or with solid Neon. They are then accumulated in a Penning-Malmberg trap (Oshima 2004). The Ps target should reach a density of 10^{12} cm^{-3} during the passage of the $\bar{p}$ bunch. This target is formed by dumping a 3 keV e^+ beam onto a porous SiO_2 material in which the positrons bind to electrons, converting the e^+ into Ps in its fundamental state. In order to follow ELENA's repetition rate and reach the required Ps density, an intense source of positrons is necessary to collect 3×10^{10} e^+ every 110 s. To this aim, we will use a 10 MeV linear electron accelerator of 200 μA average current.

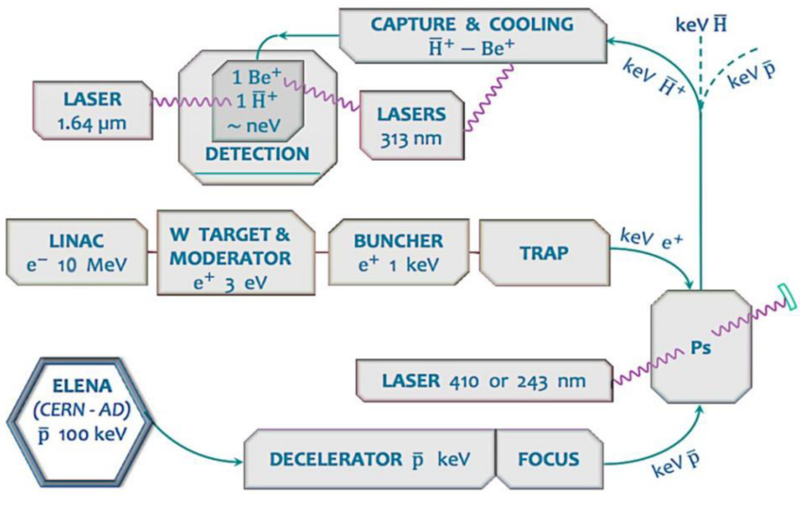

Figure 1: the general scheme of the GBAR experiments – in the area surrounded by a red line the steps qualified at the CEA Saclay development platform.

3.2. The GBAR development platform at CEA Saclay

To measure the efficiency ratios of the successive steps of the GBAR experiment a development platform has been built at the CEA Saclay. This setup allows the qualification of all the steps of the GBAR experiment down to the positronium formation. It comprises a compact electron linac, a positron generator coupled with a moderating system, a buncher to adapt the positron energy and bunch length allowing the filling of a magnetic trap. This Pening-Malmberg trap consists of a 5T superconducting magnet coupled with 20 electrodes to keep the positron confined. It has been provided by the Riken Institute in Japan.

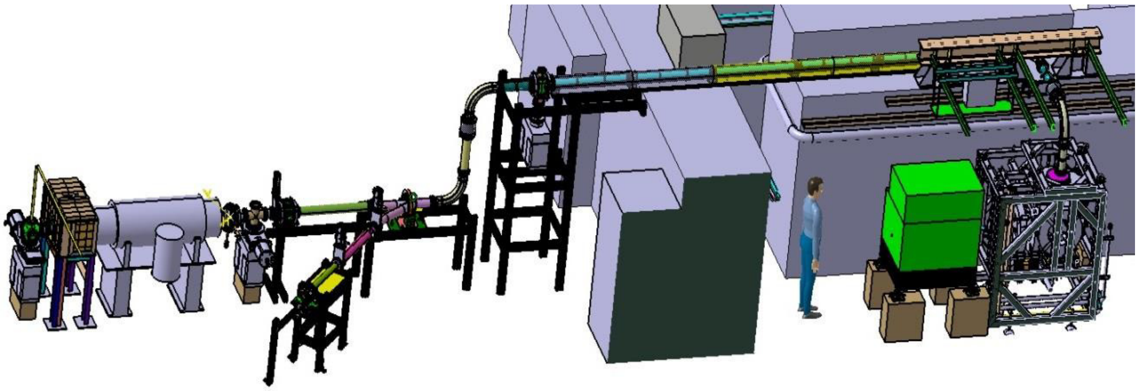

Figure 2: General view of the GBAR development platform at CEA Saclay. The electron linac is in the green box.

3.3. A compact electron linac

The primary power source for positron production is a compact electron linac, evolution of an X-Ray generator. Originally designed for 4.5 MeV electron production, it has been upgraded expecting to reach 5.5 MeV electron using a more powerful magnetron and 0.2 mA mean current thanks to an impregnated cathode. Nevertheless and after solving several youth illness the linac finally performed well. (Rey 2012)

3.4. The positron generator

The positron generator has been designed as a versatile prototype allowing the use of a conventional tungsten moderator or the development of a cryogenic neon based moderator. Due to these constraints the vacuum vessel is fairly large as the cryogenic neon moderation would not allow its positioning in the remaining electron flow after the primary target. It further imposes a dual mode for the magnetic field configuration, high field for the high energy positron extraction guided to the neon moderation, low field if the tungsten is located after the target.

3.5. Beam transport and beam bunching issues

The positron beam is guided by a 13 m long transport line consisting of a vacuum tube in which a continuous magnetic field (0.5 to 1 mT) is established by coils wound directly on the tube. This solution has been preferred to the Helmholz coil system as it is far more compact and therefore more suitable to go through the radiological shielding.

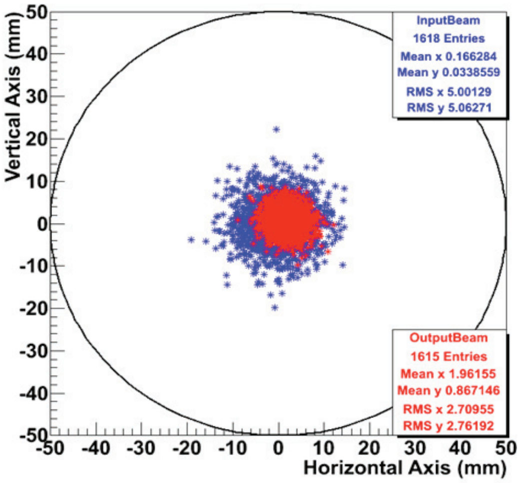

Figure 3: Positron beam size at the entrance (blue dots) and exit (red dots) of the 13m long magnetic guiding line.

A stretcher system has been integrated to the beam transport line. It is designed to suppress the time structure coming from the electron linac. It operates as a Penning Malmberg trap with low magnetic field (80 G), consisting of a long central electrode to accommodate the entire positron pulse and two end electrodes acting as entrance and exit gates. Once the entire positron pulse has filled the central electrode the entrance gate is closed, the pulse being captured between the two gates electrodes. The exit electrode opens then by reducing slowly its voltage. This spreads the entrance pulse of 2.5 µs over a 5 ms period corresponding to the 200 Hz linac frequency, as illustrated on figure 4.

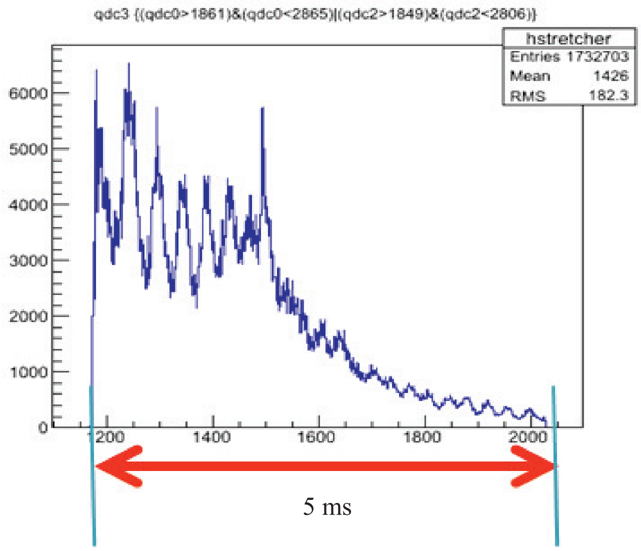

Figure 4: Effect of the stretcher. The initial beam of 2.5µs is distributed over a 5 ms period, leading to a quasi continuous beam over 2.5 ms.

3.6. Positron storage

As explained in section 3.1, in order to create antihydrogen ions, it is necessary to produce a dense cloud of positronium with which the antiprotons from the AD-Elena ring interact. The positronium cloud is made by dumping a bunch of positrons of a few keV onto a porous silica material. Given the antiproton / antihydrogen / positronium reactions cross-sections, a positronium cloud of around 7×10^{11} cm^{-3} density is needed. It can be produced by dumping 2×10^{10} positrons in less than 100 ns onto the positron-positronium converter. This operation has to be repeated at each extraction of the antiprotons, i.e. every 110 s.

These numbers set the slow positron flux needed for the experiment (2.8×10^{8} e^{+}/s), given the positron-positronium conversion efficiency of 35 %. These positrons are accumulated during 110 s in the high magnetic field Penning-Malmberg trap of the RIKEN Atomic Laboratory, presently installed and running at Saclay. It consists in a superconducting magnet producing a very uniform 5 T magnetic field in the trapping region. The trap is made of 23 ring electrodes with which one can form two electrostatic potential wells of opposite signs with a depth of up to 1000 V, one to store electrons emitted by a cathode upstream of the trap, the other one to accumulate the slow positrons from the linac. The electrons are loaded before the positrons are accumulated; they cool by synchrotron radiation to a few K. These cold electrons are used to slow down the positrons which go back and forth through the electron plasma and which eventually fall into their capture well when they have lost enough energy. With an electron plasma of 10^{17} e^{-}/m^{3}, this process takes ~ 3 ms, allowing a maximum repetition rate of 300 Hz for the LINAC.

Positrons are guided from the linac to the trap by a 100 G magnetic field. When they approach the trap entrance, they encounter a strong magnetic mirror. It is necessary to accelerate them to 1000 eV to overcome this mirror. Fast switching of an additional electrode upstream of the trap allows the capture of the positron bunch: it is at a low value when positrons arrive, and raised before the positron is reflected back from the bottom end of the potential well. Since, the positrons make such a round trip in the trap in less than 100 ns, the initial 4 µs bunch from the linac has to be compressed by a factor ~50 so that a full bunch can be captured.

This accumulation scheme is new. It cannot be used with positrons issued from a radioactive source which produces a continuous beam. The method must thus be settled at Saclay, before the Penning trap is sent to CERN. The principle of the method has been demonstrated by Grandemange (2013), and is illustrated in figure 5, with a very low efficiency, and the many parameters of this accumulation scheme are now being optimized to approach the expected performances.

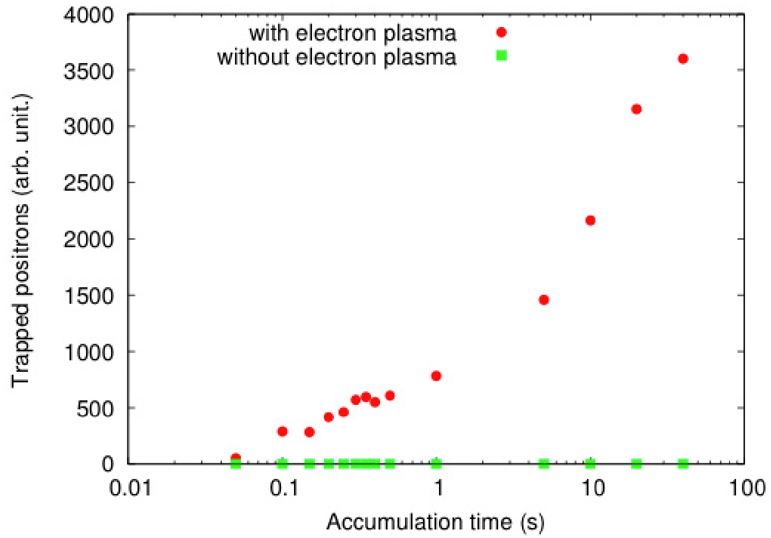

Figure 5: Positron storage. Accumulation of positrons with time (red dots) only happens once electrons are preloaded in the trap. Without the electron plasma, the positron signal does not increase with time (green dots).

3.7. Positronium spectroscopy

As the production of positronium is a critical path for the GBAR experiment a dedicated spectrometer has been built to study the condition of its production. Positronium, a bound state between a positron and an electron, is a quasi atom having two states, para-positronium of short lifetime (125 ps), and ortho-positronium of longer lifetime (142 ns). Positronium is formed in the interaction of positron with porous matter when porosities have the appropriate size. Thin layer of porous silica allows a production efficiency of more than 40% of free ortho-positronium per incident positron.

This spectrometer can also be used as a non destructive porosity characterization system. It allows measurement of open or closed porosities. It also proved the usability of the positron generator for materials science applications.

4. Positron generator developed for materials science laboratories

The positron generator technology developed at CEA Irfu is in the process of being industrialized and commercialized by a start up company "POSITHÔT – the anti matter manufacture". Designs based on the GBAR know how have been extrapolated to provide up to 2 to $3x10^7$ slow positrons per second. An order of magnitude more can be expected using a cryogenic neon moderator, nevertheless the intrinsic energy spread due to neon moderation generates a larger beam of positrons which is more difficult to handle than after tungsten moderation.

The first high flux positron generator will be installed in the CNRS CEMHTI laboratory in Orléans (France). The positron generator will be completed by a beam splitter to allow four simultaneous materials science experiments. The option of keeping the full positron flux on the same target will nevertheless be preserved to ensure the development of positron microscopy.

5. Conclusion

CEA-Irfu has developed an innovative compact, non radioactive, linac based positron generator for the need of the GBAR experiment. This fundamental experiment will measure the behavior of anti-hydrogen in the gravitational field of Earth. The experimental positron generator built at CEA-Irfu works now efficiently after several years of fine tuning. The GBAR experiment will be installed at CERN during 2016, using an upgraded version of the positron generator. In parallel to the applications for fundamental physics, a startup company "POSITHÔT – the anti matter manufacture" is under creation to satisfy the need of materials science laboratories willing to improve their capabilities in defect analysis. This company will provide positron generators, based on the CEA-Irfu technology, in the intensity range from $5x10^6$ to $5x10^7$ slow positrons per second in a first time, and increase by a factor 10 the highest positron flux available in a near future. The first of these generators will soon be installed at the CNRS CEMHTI laboratory in Orléans (France).

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