Design of the Slow POSitron faciliTy (SPOT) in Israel

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Abstract. A slow positron beam is being built in the Hebrew University, the Slow POSitron faciliTy (SPOT). In Israel, the beam will introduce a new tool for both fundamental and applied research. Here we present the design process of the beam, where the leading goals are safety and high efficiency, with a flexible choice of the positron source. The challenges in the design of a moderator unit, based on frozen Neon, the pre-accelerator section and the full beam-line were addressed by simulation programs using various packages: COMSOL, SIMION and GEANT4. First measurements in SPOT are expected within a year.

1. Introduction
Positron Annihilation Spectroscopy (PAS) is a well-established method used in the fields of solid-state physics, chemistry, materials science and materials engineering [1]. The two most common PAS measurement systems are based on table-top gamma spectrometers, and slow positron beams. The operational concept of most slow positron beams is similar: high-energy positrons emitted from a $\beta^+$ radioactive source are moderated, low energy positrons (few eV) are then selected and re-accelerated to create a mono-energetic positron beam with controllable energy that varies from several tens of eV up to several tens of keV [2]. The physical implementation of this concept varies from beam-to-beam mainly in the choice of moderator material (frozen gas vs. metal with negative e$^+$ work function), in its geometry and source coupling, and in the details of the slow positron selection and re-acceleration technique. The final beam efficiency, defined as the ratio of the number of mono-energetic positrons impacting the target to the source activity, strongly depends on the exact beam design and varies from $\sim 10^{-4}$ to $\sim 10^{-2}$ [3].

We are currently building the first slow positron beam in Israel. The beam will be the center of the newly formed Slow POSitron faciliTy (SPOT) at the Hebrew University. This beam, together with the PAL spectrometer available in Israel [4], will bring new material research capabilities to the Israeli community. The SPOT positron beam will serve as a tool for both fundamental and industry-oriented applied materials research.

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2. Design of the SPOT Positron Beam

The SPOT beam was designed under several safety guidelines: (1) Use high efficiency frozen gas moderator to considerably reduce the required positron source activity, (2) Allow usage of short-lived positron source to avoid long term contamination hazard, and (3) Use an isolated electrostatic beamline that operates on a high-voltage platform, while keeping both the source chamber and target at zero potential. Additionally, we want the design to allow for a simple usage with either short-lived or long-lived positron sources. A cross section of the SPOT beam design is shown in Fig. 1. The design is such that positrons emitted from the source pass through a frozen gas moderator, which is kept at ground potential. The low energy positrons are then pre-accelerated to 50 eV on a high-voltage platform. A 90° bend section select the slow positrons and filter out higher energy positrons. The final positron acceleration is done by a 10-step acceleration unit, while the target (sample) is kept at ground potential. A constant low magnetic field, produced by a set of solenoids, is applied along the beam line, keeping the positrons focused along the beam direction.

Overall, the SPOT beam is designed for both safety and ease of use. All high voltage elements will be internal to the beamline and moderator structures. The beamline has been designed to allow changing the beam energy without changing any of the magnetic fields that collimate and bend the beam.

Figure 1: Top view of the cross section of SPOT design scheme. The source and beam propagation direction are marked in yellow. The moderator chamber (A) contains the moderator (B) and a pre-accelerator section (C). The beam-line consists of three parts. The first (D), from the exit of the moderator chamber to the acceleration unit (E), is made of concentric pipes. Coils, in blue, form a uniform magnetic field along the beam direction. Helmholtz coils are used to maintain the same field inside the moderator chamber, in the target chamber (Not shown) and to bend the direction of the beam in 90° (F).

2.1. Positron source

The primary driver of SPOT’s design is to make it a useful tool for the materials industry. As such, we examine the ability to use short lived positron sources, such as $^{18}$F (half-life of ~110 minutes). This source is commonly used in PET imaging and is therefore well regulated legally and is readily available wherever PET imaging systems are in use. By using a short-lived source, a short term highly active source can be used to increase the positron flux on target. More importantly, due to its short half-live, the radiation hazard is limited only to the time of measurements. Efforts are currently made to develop the process of source production, in a dedicated source container, and the method of safely handling it in order to position it in the moderator chamber.

2.2. Positrons moderator – challenges and solutions

Comparative studies show that frozen gas moderators (especially Neon) have a much higher moderation efficiency compared to tungsten foil moderators [5]. Therefore, to reduce the required source activity, the SPOT beam will use a high efficiency frozen gas moderator. The moderator design combines both transmission and reflection geometries. It consists of a copper mesh window and a conical shaped, oxygen free copper piece, coupled to a cold head. The oxygen-free copper is an excellent thermal conductor and therefore the gas is expected to freeze on its surface and on the mesh. The conical shape is expected to further enhance the efficiency [6]. One disadvantage of frozen gas moderators is that positrons thermalize via scattering processes, and thus exit with wider energy distribution compared to that of positrons moderated in tungsten [7]. Similarly to other slow positron beams [2], a pre-acceleration unit will give the moderated positrons an initial low energy, of 50 eV, with which they can pass the bending section of the beam. The main challenges in the moderator
design relate to the questions of how to keep low temperature in the vicinity of the frozen gas, near the active positron source, and how to mount the pre-accelerator close to the moderating unit and apply voltage to them. A design that addresses both requirements was developed using the COMSOL and SIMION simulation packages [8,9]. The first was used to simulate the temperature profiles in the vicinity of the moderation unit, with the influence of other neighbouring materials and the positron source, whereas the latter was used to design the geometry of the pre-accelerator unit. Fig. 2 shows the spatial and energy distributions of the accelerated positrons, as produced by the SIMION simulation. The pre-accelerator will consist of few ring shaped electrodes, separated by rings of insulating Teflon. Voltage to the rings and to the copper unit will be applied by wires with feed-through connections to the vacuum chamber. In order to keep the entire cold-head grounded, a sapphire spacer is added between the cold head and the pre-acceleration unit. We choose to use sapphire as, at low-temperatures, it is a good electrical insulator as well as a good thermal conductor.

**Figure 2:** Left: A scheme of the pre-acceleration unit within the moderator vacuum chamber, showing positron trajectories calculated by SIMION for the shown setting. Right plots: Spatial (left) and energy (right) distributions of the same positrons. The energy shown is ~28keV, with FWHM of ~3eV. This simulation was performed before the bending was introduced.

2.3. The design process of the beam line
The electrostatic beam-line uses magnetic and electric fields to select moderated positrons and transport them from the moderator to the target, while accelerating them to the desired energy (see Fig.1). The beam-line is designed such that the target (sample) is kept at ground potential. This reduces the hazard of electrical shock at this readily accessible position. To allow the target to be kept at ground potential, all units upstream of the acceleration unit have to be kept on high-voltage platform, where the high-voltage is defined by the final positron acceleration voltage. This means that the moderator assembly and the pre-accelerator unit, as well as the bending section, should all be kept at high-voltage. Because of the uniform base voltage, the pre-acceleration of low energy positrons and their selection by the bend is indifferent to its absolute value. The demand of keeping the moderator chamber at ground potential, but the outgoing positrons at high potential presented a complicated design challenge. The solution chosen is to use two concentric tubes from the exit of the moderator to the accelerator unit (see Fig. 1). The inner tube will be held at high potential, while the outer tube will be grounded. This scheme required a special design of the inner tube, such that the vacuum within it can be maintained. A constant solenoid magnetic field of ~9 mT will be applied along the beam-line, which will collimate low-energy positrons along the beam propagation direction. In the 90° bend section, a transverse magnetic field will be used to bend the low energy positrons in the beam direction and to filter them from positrons with higher energies. A 10 step acceleration unit, downstream of the bend, will accelerate the particles from the desired voltage to zero. The planned HV will vary from 50 eV to 30-50 keV. The exact field configuration was determined following extensive beam-line simulation work, using two packages: GEANT4 and COMSOL [10,8]. The first, GEANT4, was used to define the constant magnetic field along the beam and a perpendicular field in the bending section, in accordance with the possible geometry in the laboratory room. Lead by the design of the coils at the SPONSOR beam [2], we calculated the structure and number of coils needed for the SPOT beam, as well as the required currents, to perform the uniform magnetic field of ~9 mT. COMSOL, a multi-
physics solver program includes a beam-line simulation package. Its inputs are realistic physics observables, such as coils current and electric potential, and the program solves for the resulting electric and magnetic fields. A complete magnetic field map, including fringe fields, is calculated. These fields are then used to calculate more precisely the transport of the particles from the moderator to the target, as shown in Fig 3.

Figure 3: Left: details of magnetic field magnitude along the beam-line, calculated by COMSOL. Right: positron trajectories, calculated by COMSOL, being transport from the source, through the beam-line, to the target position. Colors represent positron energies, from low (blue) to higher (red) energies.

3. Summary
The design of the SPOT beam provided many challenges for which we developed realization concepts and designed solutions using the simulation packages COMSOL, SIMION and GEANT4. To gain high efficiency the design is based on frozen Ne as a moderator. A special pre-accelerator unit mounted within the moderator chamber will extract the moderated positrons and direct and focus them into an initial beam. Outgoing mono-energetic slow positrons, with energy of ~50eV, will be selected for further acceleration by a bending section. The acceleration to the target will be done by a 10-step acceleration unit. Coils along the beam will form a constant magnetic field of ~9mT in order to keep the positron trajectories spiral along the beam direction. Safety considerations led to a design of a grounded target and a high voltage platform internal to the moderator chamber and to the beam line, while all outer parts are kept at ground potential too. The design allows usage of either $^{22}$Na source, available to purchase, or custom made $^{18}$F source which, due to its short half-life, presents much less safety requirements. The implementation of the moderator assembly and the beam line are under-way. First measurement with the SPOT beam is expected in the coming year.

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