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Intense Source of Slow Positrons

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Executive Summary

We propose to build an intense source of slow positrons which could be the basis for a series of experiments in fundamental and applied research and would also be a prototype source for industrial applications. A non comprehensive list of experiments concern 3D imaging of molecules, a gamma-ray laser, non-neutral plasma physics, and experiments on gravity with positronium (Ps) and spectroscopy with anti-hydrogen ($\overline{H}$). Industrial applications concern the field of defect characterization in the nanometer scale. We describe a layout for a source of positrons based on pair production with a beam of electrons from a 10 MeV accelerator hitting a thin target at a low incidence angle. The positrons are collected with a set of coils adapted to the large production angle. The collection system is designed to inject the positrons in a Greaves-Surko trap [1].

Gravitation is the only fondamental interaction for which experimental data with single elementary neutral particles are very scarce and data with antimatter non existant. The free fall of hydrogen or positronium atoms are the first two experiments in particle physics that this facility allows. Furthermore the production of hydrogen and anti-hydrogen is fully symmetric in this apparatus: once the experiment with hydrogen is operational, the replacement of protons with antiprotons from a trap will allow the first observation of the gravitation interaction on antimatter with a single neutral atom.

An ongoing research program at UC San Diego is developing the next generation trap to cool and store $10^{12} - 10^{13}$ positrons. This trap is expected to be operational in 3 years from now. Our proposal is parallel to this program and spans the same period of time. The two projects would then join effort and create a positron facility. The foreseen facility is of the same type as a synchrotron radiation facility but much smaller. It is operated in time sharing mode between several small experiments open both to fundamental research and applied physics. A short memo from Prof C.Surko can be found as an appendix to this proposal.

Keywords:
positron; positronium; accelerator/linac; defect characterization; 3D molecule imaging; energy storage; gamma ray laser; matter antimatter symetry; antigravity;

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1 Introduction

The apparatus presented in this proposal is a small facility for interdisciplinary experimental studies with positrons.

The interested fields are high energy physics (HEP), biophysics and condensed matter physics.

In HEP, our aim is to produce positronium (Ps), hydrogen and antihydrogen in a symmetric way in the same experimental conditions. This will allow gravity and spectroscopy experiments to compare matter and antimatter. Measurements are being made at CERN with the atomic spectroscopy of anti-hydrogen [2]. A gravity experiment is being studied at CERN on anti-hydrogen [3] and in the US on positronium [4]. In all cases a high intensity positron source is necessary.

A novel method to produce a 3D image of molecules with a resolution of few Ångströms has been proposed [5]. This method relies on the availability of a very intense source of positrons. If implemented, we believe such a method would open new possibilities for biophysics studies.

Since several years the possibility to create a Bose-Einstein Condensate (BEC) of positronium and to make a 511 KeV gamma ray laser is being studied [6] [7]. The main obstacle until now has been the lack of an intense source of slow positrons.

Moreover a high production rate of slow positrons (exceeding $10^{10}s^{-1}$) and of positronium is being looked for in industrial and research applications. Let us cite, for instance, "Positron Annihilation Spectroscopy" (PAS) [8].

The most commonly used source of positrons is ^{22}Na. Such compact sources are well suited for laboratory research, but their maximum activity lies around 4 10^9 Bq with a mean lifetime of 2.6 years. There are also some accelerators (100 MeV) partly used for the production of slow positrons which are managed as a facility.

We propose to replace these sources with an intense ($> 10^{12}s^{-1}$ source of slow (MeV) positrons based on e^+e^- pair creation through the interaction of an electron beam on a target. The energy of the electron beam is 10 MeV with an intensity of a few mA. This source was designed to be coupled with a Greaves-Surko trap [9] in order to produce a bright beam of slow positrons (meV to KeV). It may also be used to produce positronium by applying the beam onto a cristal [10].

This setup would be a dedicated facility, the size of which is comparable to a radioactive source but requires a special building for shielding. Such an apparatus is much smaller than the large 100 MeV linacs used up to now and would provide superior performance in intensity and brilliance.

The pair production cross section increases with energy. However the development of such a setup for university or industrial applications limits the beam energy to 10 MeV because a higher energy would start to activate the environment (legal limit).

The first part of this note lists the main experiments in fundamental and applied physics we foresee with such a source. The second part describes the system of production and collection of MeV positrons developed by CEA-Saclay. The third part lists competing methods.

2 Science and Frontier Technology with an e^+ Facility

The facility is similar to a synchrotron facility, but much smaller. The facility is to be operated in time sharing mode: some users will develop molecule imaging, others e^+e^- lasers and HEP physicists will recombine matter and antimatter.

2.1 Gravity and Spectroscopy with Ps, H and $\overline{\mathrm{H}}$

Experiments on gravitation are the most important goals in fundamental interaction research which underlie this proposal.

The detection of deviation from gravity by measuring the free fall of Ps or $\overline{\mathrm{H}}$ neutral atoms in the gravitational field of the earth requires the making of a slow beam of such atoms.

Positronium is relatively easy to produce, but has a short lifetime. High Rydberg states of Ps could live of the order of 1ms. A proposition to study the fall of Ps [4] describes a way to produce thermal Ps atoms (3 km/s maximum speed) which are then excited with Doppler-free two photon techniques. The emitted atoms are focused by a mirror and converge on a 1 μm spot while the deflection expected from gravity is 50 μm on a 10 m scale. Only a few atoms are needed to establish the deviation, but the rate of slow positrons needed in order to achieve a 5 standard deviation measurement in a week of run is of the order of $10^9 s^{-1}$. This is three to four orders of magnitude more than what is achieved with a 100 mCi Na^{22} source with a moderator, but corresponds to the nominal production of the apparatus we propose.

In order to form anti-hydrogen atoms, the classical radiative recombination reaction (RR): $e^+ + \overline{p} \rightarrow \overline{H} + \gamma$, may be used as was done for hydrogen recombination. The cross section to produce H in the ground state is 1.676 $10^{-22}(13.6/E_{e^-})$ cm^2, where E_{e^-} is the kinetic energy of the electrons in eV. The cross sections for the excited states are in the ratio of n=1:2:3 and rate=1:0.55:0.38. This reaction requires a very well defined and very low relative velocity between the positrons and the anti-protons. Furthermore it requires an unachievable density of e^+. If a pulse of 10^6 $\overline{\mathrm{p}}$ and a pulse of e^+ of density 10^{14} cm^{-3} travel at the same speed and have a temperature of the order of 1 meV, one expects the formation of 600 $\overline{\mathrm{H}}$ atoms in a 1m long reaction chamber with 100 KeV kinetic energy.

It is possible to increase the formation rate with a gain of the order of 100 with the use of extra laser photons (LIRR) : $e^+ + \overline{p} + \gamma \rightarrow \overline{H} + 2\gamma$. In order to perform a free fall experiment the beam would have to be slowed down.

The preferred channel for the apparatus we propose is another reaction: $Ps + p \rightarrow H + e^+$. This reaction was experimentally demonstrated [11]. It is expected that the charge conjugate reaction producing anti-hydrogen has the same cross-section. The cross-section is as high as 10^{-15} cm^{-2} when a 10 KeV pulse of protons interacts with thermal Ps atoms. This is three orders of magnitude greater than for the RR process. In this reaction, the positronium acts as a target in the laboratory frame and the proton or antiproton as the beam. Having an intense source of positrons allows to make this beam with a limited number of antiprotons which would be produced elsewhere and stored in a trap.

The reaction on positronium, allowed by the intense positron beam, will convert a proton or an antiproton into H or $\overline{\mathrm{H}}$ with an efficiency above 10 %. Therefore experiments on antihydrogen will be possible with as few as 10^6 antiprotons stored in a trap. Furthermore some of the atoms produced will be converted into ions through the reaction: $H + Ps \rightarrow \overline{H}^+ + e^-$. Recent studies have shown that the optimal incident p or $\overline{\mathrm{p}}$ kinetic energy is 10 KeV [12], which can easily be achieved at the exit of a trap. These ions can be decelerated and captured in a trap where the e^+ can be removed and the free fall observed.

The experiment is fully symmetric with respect to electric charge and can be tested and optimized with readily available proton beams of 10-20 KeV before launching a more expensive effort with antiprotons.

Antiprotons produced at CERN have been trapped [2]. An antiproton facility is foreseen in Darmstadt, Germany [13].

Once the experiment with protons is operational, the development of a transportable trap with 10^6 antiprotons is the main task left before observing differences between H and $\overline{\mathrm{H}}$ under the same conditions.

Among other spectroscopy techniques, the possibility to make the Separated Oscillatory Field measurement of the 2S-2P transition is being investigated. The publication of references [14, 15] presents this technique. It is well adapted to the beam conditions of the apparatus presented here.

2.2 Bose-Einstein Condensation and Gamma-ray Laser

Liang and Dermer [7] suggested to create a BEC of positronium and to use it to make a 511 KeV gamma ray laser. Two ways to create this BEC were investigated. One of them relies on the laser cooling of the Ps gas. In 1988 when the article was published, the cooling technique was not well developed and an intense e^+ source was lacking: such an experiment can now be reconsidered.

Alternative paths were studied. In 2002, A.P. Mills [6] revisited the idea of creating an annihilation photon laser. A gas of Ps is created inside a cavity of 1 mm length and

200 nm radius in a solid and cooled to 100K. When 10^{12} atoms are created in this cavity, a Bose-Einstein (BEC) of Ps should occur. Then the annihilation photon pulse would be initiated by a pulse at the hyperfine transition frequency. The steps to reach this goal are difficult but seem achievable. The first requirement is an intense source of positrons with a capacity to store $\approx 10^{12} e^+$.

It would take several weeks to accumulate such an amount of positrons with conventional sources while it will take less than thirty minutes with the proposed facility.

2.3 3D imaging of molecules

In 2001, Mills and Platzman [5] proposed to use positrons for the 3D imaging of single molecules at an atomic scale. The idea is that the positron cross-section is much higher (factor $\approx 10^4$) than that of X rays. When positrons of a few KeV traverse a Ni single crystal foil with negative affinity for positrons, (100 nm thickness), positrons of ≈ 1 eV (i.e. a 0.2 nm wave length) are reemitted as a quantum wave with a coherence length of at least 10 nm for a foil kept at a few degrees Kelvin. When molecules are deposited on the foil surface, the reemitted e^+ are scattered from the atoms that make the molecules. The resulting speckle pattern can be recorded on a screen placed a few centimeters from the foil. These authors estimate that 10^7 counts on the screen are necessary and that this is possible with 10^9 positrons. They also compute that the electrons ejected from the molecule will be replaced fast enough by the electrons from the metal keeping the molecule from being damaged. The rate of positrons from the source we propose would allow to get an image of a molecule in a few seconds.

2.4 Non-neutral Plasma Physics

The plasma physics interest is briefly described in the memo of Prof C.Surko which is presented as an appendix.

2.5 Other Fundamental Research

Apart from the possibility to measure the fall of Ps or anti-hydrogen in the gravitational field of the Earth which would test ideas on antigravity, or the possibility to create a Bose-Einstein condensate of positronium, we mention some research subjects which Allen Mills has enumerated for the future:

- Measuring many-body decoherence effects associated with slow positronium quantum sticking to a cold solid surface.
- Ultra precise measurement of the internal structure of positronium via its 1S-2S energy interval.
- Making the Ps_2 molecule.
- The formation of coherent positronium beams via positronium jets
- The operation of a mm-wave positronium maser.

2.6 Applied Research and Industrial Applications

New technology developments in applied physics require intense sources of cold and tunable positrons. A short overview is given here.

Materials diagnosis:

Positron annihilation is sensitive to the density of electrons. Small changes in electron density are detected, for example, when the material expands thermally. Vacancies, i.e, single atoms missing from the lattice, with low electron density are very easily detected. Concentrations of vacant atomic sites of 1 appm are already observable.

Since Positron Beam Analysis is a contactless method the sample can be heated to very high temperatures and still be examined. Vacant sites can also be introduced at any temperature by mechanical deformation, deposition processes (sputtering, etc.), and ion implantation.

The tunable energy of the positron beam is used to obtain depth resolved information on thin layered structures or samples with a non-uniform defect distribution. The depth resolution amounts to 10%. Positron beam analysis can be successfully used to monitor defects at interfaces between thin layers. In oxides of electrical devices, e.g., MOS structures, electrical fields can be used to drift the positrons to the interface of interest.

Vacancy clusters or voids (0-0.5 nm) can be observed easily by changes in the Doppler broadening and lifetime of annihilating positrons. For larger voids observation of the formation of Positronium provides evidence of the presence of voids and yields size information. Lifetime measurements of annihilating ortho-positronium give information on voids with sizes up to 20 nm. In very large pores ortho-Positronium survives sufficiently long so that three-gamma annihilation occurs. This can be monitored by measuring three-gamma contributions to the annihilation lifetime and energy spectra. Very high resolution (5 times that of Doppler broadening) is obtained with the aid of the 2D-ACAR setup.

Abbreviations:
ACAR(Spectroscopy using Angular Correlation of Annihilation Radiation)
PAES (Positron-Annihilation Induced Auger Electron Spectroscopy)
PALS (Positron-Annihilation Lifetime Spectroscopy)
AMOC (Age-Momentum Correlation Spectroscopy)

The following explanations on some of the techniques for applied surface science are copied from the web site of FPSI [16].

- PRS:

  Positron reemission spectroscopy (PRS)-This technique is based on the phenomenon that thermalize and be reemitted because many solids possess a negative work function for positrons. The energy of the reemitted positrons can be analyzed to yield the types of contrast that are not available with conventional scanning electron microscopy. The technique has the ability to distinguish non-uniform film thickness, varying crystal orientations, differences in bulk defect density, concentrations of adsorbed molecules, and contaminant layers.

- PAES:

  Positron annihilation induced Auger electron spectroscopy (PAES)- This technique is analogous to electron induced Auger electron spectroscopy (AES), except that the core hole, which leads to the ejection of the Auger electron, is created by positron annihilation rather than electron impact. For this technique, positrons are injected at low energy into the surface to be analyzed. The ejected electrons are analyzed in the usual way using an electron energy spectrometer, but the measurement is substantially simplified because of the absence of background high-energy secondary electrons.

- REPELS:

  Re-emitted Positron Energy Loss Spectroscopy (REPELS)-In this process, low energy monoenergetic positrons bombard the surface to be studied, and those that are reflected inelastically are energy analyzed. Energy is lost by transfer to vibrational modes and electronic state transitions of the surface and surface-absorbed molecules.

- LEPD:

  Low-Energy Positron Diffraction (LEPD)-For this technique, a crystalline sample is bombarded with low-energy (0-300 eV) monoenergetic positrons. Because of the low energy, there is relatively little penetration into the sample, and the diffracted positrons backscatter, producing spots on a fluorescent screen. The positions of the spots are a measure of the sample's diffraction sites. This information can be used to determine the crystal structure of a clean substrate or to analyze an adsorbed layer.

- PIIDS:

  Positron Induced Ion Desorption Spectroscopy (PIIDS)-This relatively new technique uses time-of-flight mass spectrometry to measure the mass spectrum of ions desorbed from surfaces by the injection of positron pulses. The ion desorption rate due to positron injection is much larger than that for photodesorption.

- PALS:

  Positron Annihilation Lifetime Spectroscopy (PALS)-Positrons injected into surfaces can be trapped and subsequently annihilate in vacancy-type defects. For high-enegy positrons obtained directly from 22Na, the lifetime, can be measured by recording the time delay between the prompt 1.2 MeV gamma ray that is emitted by the nucleus simultaneously with the positron, and the 511 keV annihilation gamma rays. This technique has been extensively applied to the study of bulk properties of solids. One of the most important current applications of lifetime spectroscopy is the analysis of microvoids in semiconductors and polymers. This technique is the most sensitive one available for studying voids in solids, and can provide information about both the size and concentrations of voids. The technique has been applied to characterizing the properties of semiconductors, such as ion-implanted silicon to study, for example, stress voiding and electromigration. One of the most important current areas of research is the study of the properties of polymers. Positron lifetime spectroscopy is capable of measuring the free volume fraction and microscopic size distribution of voids, which determine such properties as impact strength, gas permeability and aging characteristics. Another important topic is the development of low-k dielectrics in microelectronic fabrication. Such dielectrics are essential for increasing CPU speeds, and can be characterized using lifetime spectroscopy in a way that is not possible using any other available technique.

- VEPLS:

  Variable Energy Positron Lifetime Spectroscopy (VEPLS)-The power of the PALS technique can be substantially enhanced by implementing it using a monoenergetic beam source rather than a radioactive source. By varying the beam energy, positrons can be implanted to varying depths so that a depth profile of void size and concentration can be obtained. Furthermore, if the beam diameter is small, it can be scanned across the surface, so that three-dimensional information can be obtained. The technique requires pulse widths that are short compared to typical annihilation times in materials (100 ps).

- PAS:

  Positron Annihilation Spectroscopy (PAS)-This technique measures the Doppler-broadening of the 511 keV gamma-ray line resulting from the annihilation of positrons implanted into solids. The required information is contained in the gamma-ray lineshape. PAS can provide the same type of information about defects as PALS and VEPLS.

3 Production of positrons

The positrons are produced by the interaction of a flat electron beam with a 50 microns target foil. The electron beam energy is 10 MeV. The angle between the beam plane and the foil is very small, approximatively 3 degrees. The positron kinetic energy spectrum is peaked at 1.2 MeV and extends to 8 MeV.

The first step in the positron capture by the trap is the moderation process. This process involves the slowing down of the positrons, the creation of meta-stable states with collective charge oscillations in the moderator and its re-emission at ≈ 1.5 eV. The moderation efficiency decreases with the incident positron kinetic energy and is negligible at a few MeV. Therefore a magnetic collector was designed to separate the positrons from the electrons while preserving the positrons with a kinetic energy below 1 MeV.

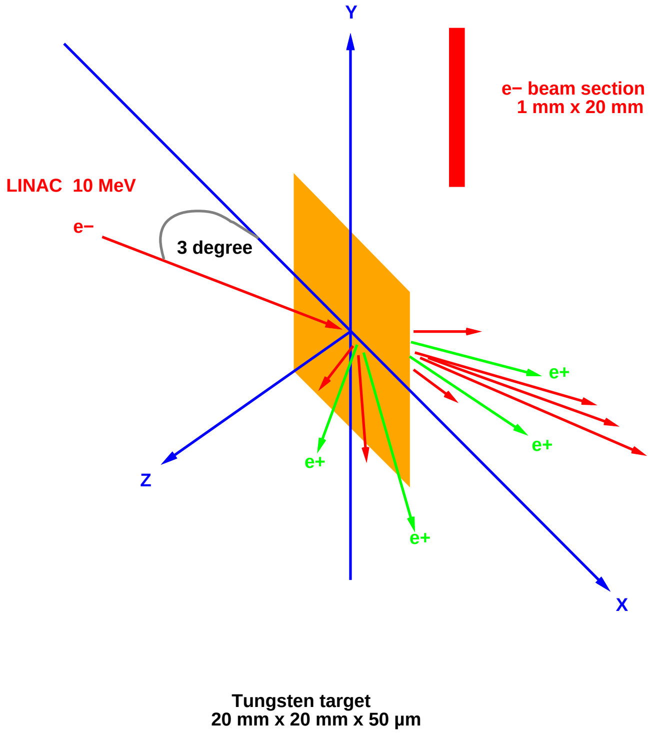


Figure 1: Diagram of the simulated target.

3.1 Target

The positron rate is limited by the heating of the target. The target material we prefer is tungsten because of its high fusion point (3695K).

At these temperatures, a thin target mostly evacuates heat via radiation. Supposing that surrounding materials are at room (300K) temperature, and using Stefan's law with an emissivity coefficient of 0.95 at these temperatures, we get for an energy deposited of 1 kW/cm^2 a temperature of 3100K when the target evacuates energy on both of its sides.

An experimental test was performed with an electron gun used to sold metal pieces. The gun delivered a beam with a diameter around 5mm, i.e. a surface of around 20 mm^2 (fig 2). The 99.99% purity tungsten target we tested had a thickness of 50 μm [18], dimensions of 5 cm x 5 cm and was held with a piece of tungsten surrounding it on three of its sides. The accelerating voltage of the gun was fixed at 40 kV, the intensity was gradually increased until perforation at 20 mA. Stefan's law would predict a temperature of 3690K, thus compatible with fusion. We have verified that a 15 mA current does not perforate the target. At 40 kV electrons deposit all their energy in the metal. The target sustains thus a deposit greater than 2 kW/cm^2. However we will keep a 1 kW/cm^2 limit on the deposited power in this note.

Even if the temperature is kept well below the fusion point, there will be metal evaporation. Using tables from Langmuir and Jones [19], on the evaporation rate of tungsten filaments for light bulbs under the Joule effect, the target would lose 10% of its mass in one hour at 3100 K, and 24 hours at 2700 K. A simple way of operation would then consist in exchanging the tungsten foil every night. This is also adequate with the running conditions with a Greaves-Surko trap, which needs to regenerate the solid neon moderator every 24 h. Running at 2700 K means a lower electron intensity and thus a reduction in the e^+ rate of a factor 1.7. We foresee a test of evaporation in conditions very similar to this project: we have agreed with the IBA [20] firm to put a target sample in one of their intense 10 MeV electron beam lines and measure the temperature rise as well as the mass loss and evaporation depth profile for foils of different thicknesses.

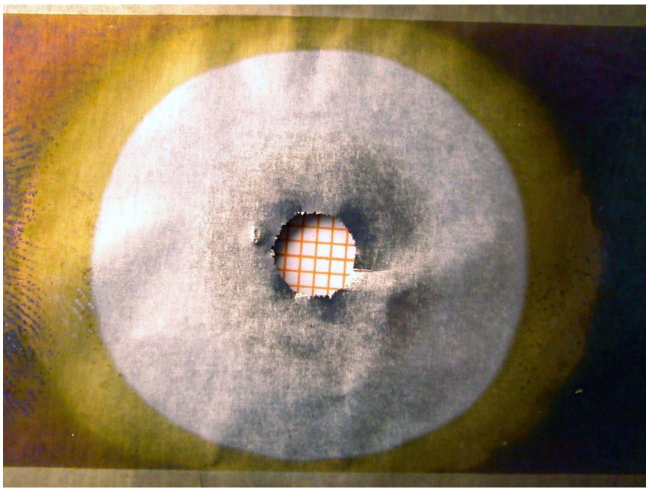


Figure 2: Perforation of a 50 μm tungsten sample under the electron soldering gun. The scale is given by the millimeter paper underneath.

3.2 Simulations

The aim of this section is to optimize the rate of positrons with less than 1 MeV kinetic energy.

3.2.1 Energy deposit in the target

We have computed the energy deposited in targets of various thicknesses with a current of 1 mA of electrons of 10 MeV with an incidence angle of 3 or 90 degrees (figure 3), with the help of the GEANT computer code [21] which is based on EGS for electromagnetic processes.

For instance, for an equivalent thickness [1] of 250 μm, the deposited power is 700 W

[1] thickness of target material crossed by electrons supposing straight line propagation

per mA. For 50 μm at 3 degrees or 1mm at 90 degrees, which have the same equivalent thickness, the deposited energy is respectively 1700 W and 4500 W. This difference is due to the fact that electrons have more possibilities to escape the target when the incidence angle is small. The path length inside the target is on average 3 times longer at 90 degrees than at 3 degrees for the same equivalent thickness.

The deposited energy increases with equivalent thickness but saturates earlier with very low incidence angle. This allows to deliver a higher intensity for the same illuminated surface. Figure 4 shows the electron current intensity which corresponds to a deposited energy of 1 kW as a function of the equivalent thickness.

At 3 degrees, let us suppose the transverse shape of the electron beam is a rectangular slit. The equivalent thickness is 20 times larger than for normal incidence. Furthermore, the illuminated surface is 20 times larger than the beam transverse cross section (figure 1). The larger surface allows a higher beam intensity than if the incidence were 90 degree with the same beam cross section.

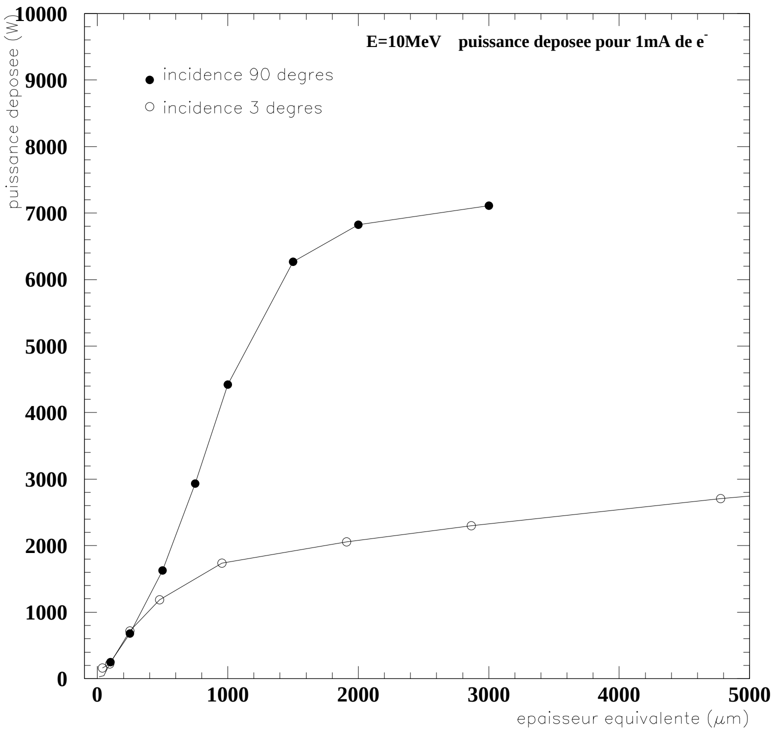


Figure 3: Power deposit as a function of the equivalent thickness crossed for 3 and 90 degree incidence angles and a beam of 10 MeV energy and 1 mA current.

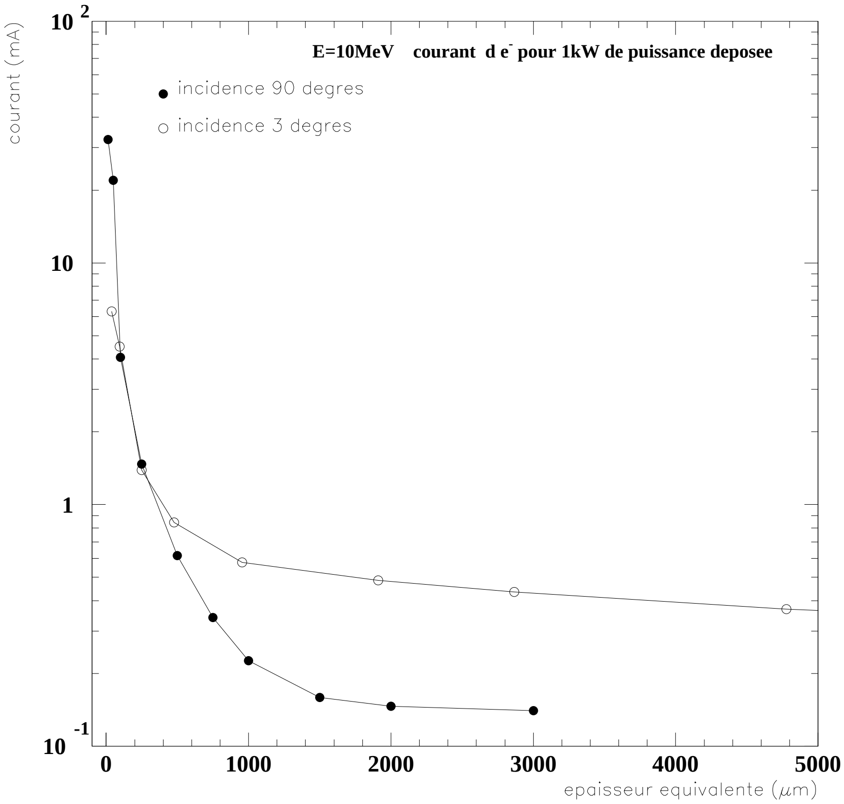


Figure 4: Electron intensity corresponding to a deposited power of 1 kW as a function of the equivalent thickness of target crossed for incident beam energy of 10 MeV.

3.2.2 Production rate

The positron rate is given in figure 5. It is of the order of $10^{13} e^+ s^{-1}$ for 1mA electron current and equivalent thicknesses between 1 and 2 mm. These results agree with an independant similar study [22]. The rate of positrons produced with less than 1 MeV of kinetic energy is shown in figure 6. It is about 1/5 of the total rate.

If we limit the deposited power to 1 kW/cm^2, this constraint determines the maximum current intensity per cm^2 of target (see figure 4). We obtain the corresponding positron rates shown in figures 7 and 8.

Let us take the example of a 1 cm^2 target of 50 micron thickness at an incidence of 3 degrees or 0.96 mm equivalent thickness. The deposited power for a 1 mA electron current is 1.75 kW (resp. 4.5 kW) at 3 degrees (resp. 90 degrees). The maximum acceptable current for the limit of 1kW/cm^2, as well as the corresponding positron rate for the maximum current are given in the following table.

Figures 7 and 8 show that these values stay valid within a factor two for equivalent thicknesses varying from 500 μm to 5 mm.

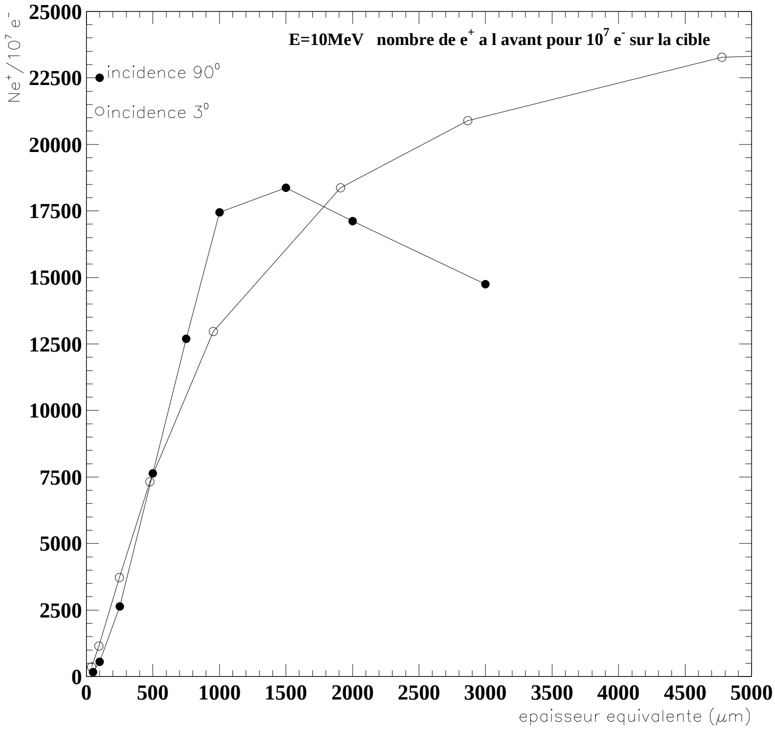


Figure 5: Number of positrons produced downstream of the target for 10^7 electrons generated as a function of the equivalent target thickness crossed for incidence angles of 3 and 90 degrees at a beam energy of 10 MeV.

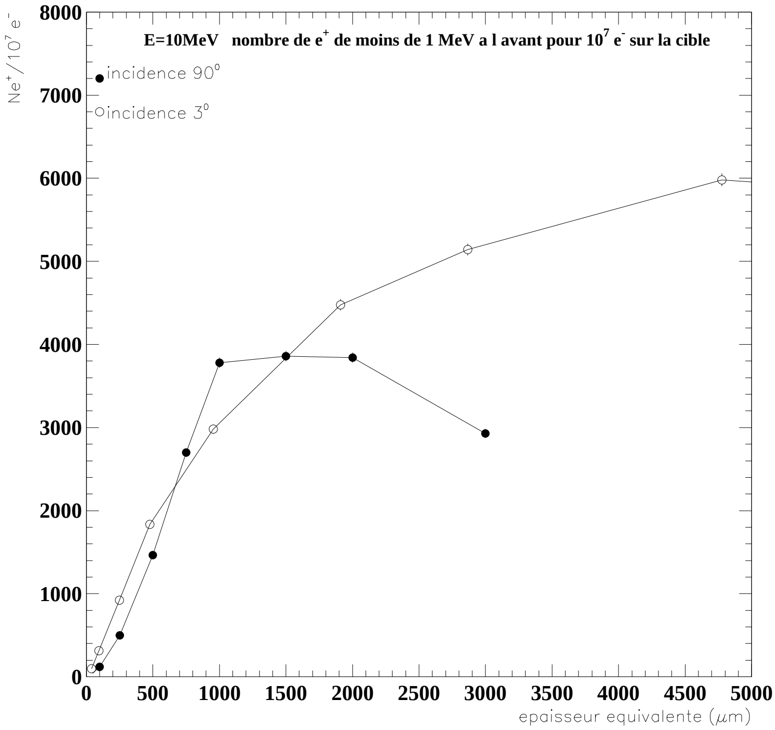


Figure 6: Number of positrons of less than 1 MeV produced downstream of the target for 10^7 electrons generated as a function of the equivalent target thickness crossed for incidence angles of 3 and 90 degrees at a beam energy of 10 MeV.

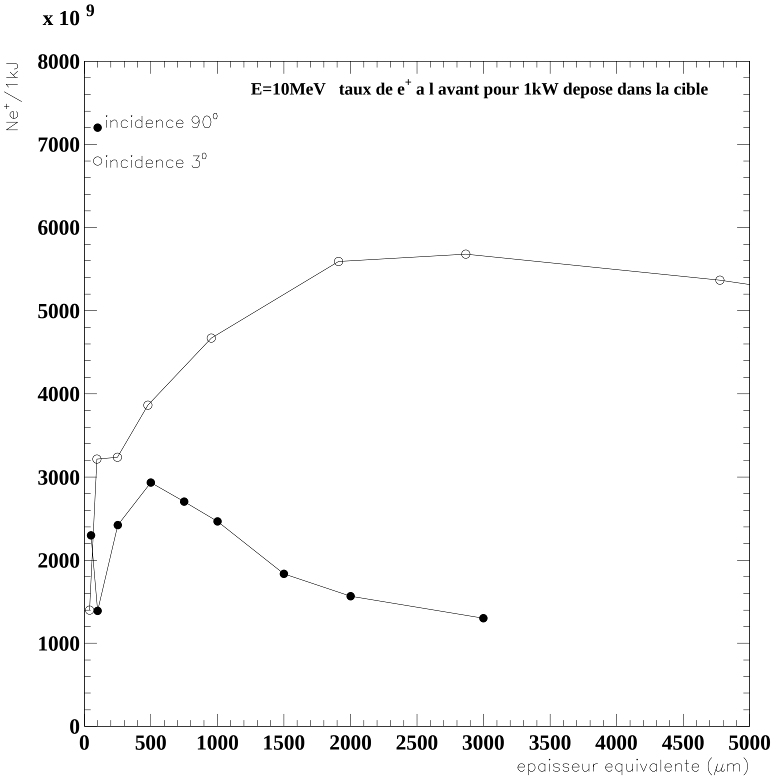


Figure 7: Produced positron rate downstream of the target for an electron intensity corresponding to a deposited power of 1 kW as a function of the equivalent target thickness crossed for 3 and 90 degree incidence angles and a beam energy of 10 MeV.

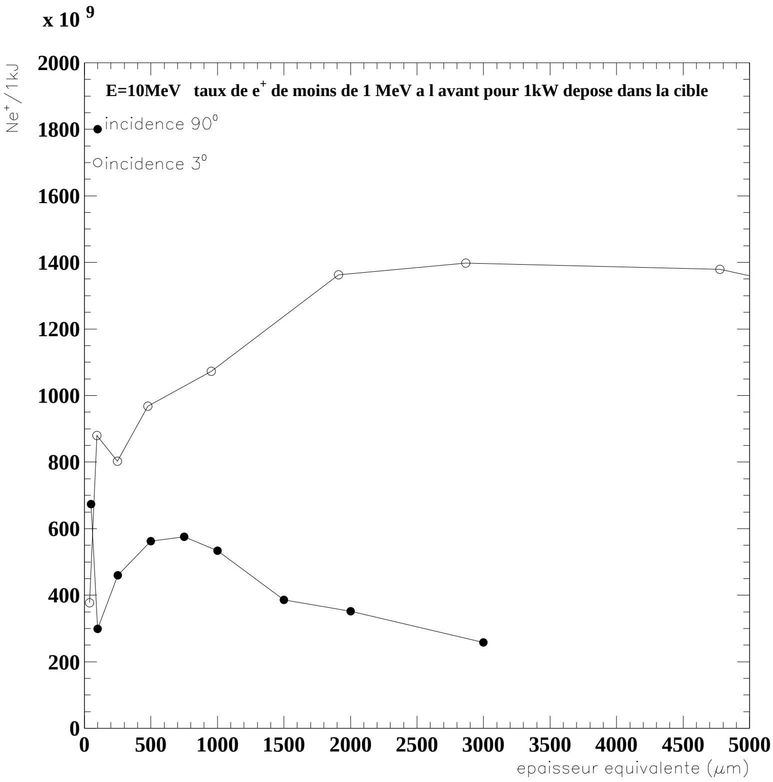


Figure 8: Produced positron rate of less than 1 MeV downstream of the target for an electron intensity corresponding to a deposited power of 1 kW as a function of the equivalent target thickness crossed for 3 and 90 degree incidence angles and a beam energy of 10 MeV.

Table 1: E = 10 MeV, target of 1cm^{2}x50 μm or 0.96mm

E=10MeV	I_{max}	Ne^+	$Ne^+(< 1\text{MeV})$
3 degrees	0.58 mA	4.6 10^{12}s^{-1}	1.1 10^{12}s^{-1}
90 degrees	0.25 mA	2.5 10^{12}s^{-1}	0.55 10^{12}s^{-1}

Active cooling by water flow is possible but with added complexity.

The above quoted production rates were normalized to a target surface of 1 cm^2. In the case of the low incidence angle, it is possible to increase the beam intensity while keeping a reasonable transverse extension of the beam, a key parameter to keep a good efficiency for the collection setup described below. In order to illuminate a target of size 1 cm x 1 cm at 3 degrees, the beam is a slit of 1 cm x 0.5 mm.

We will see in the next section on the collection of positrons that it is possible to recover a large fraction of the low momentum positrons with a target size of 2 cm x 2 cm, the beam is then a slit of 2 cm x 1 mm. The beam current needed to illuminate such a target while keeping the constraint of 1 kW/cm^2 is then 2.3 mA which produces 4.4 10^{12}s^{-1} positrons of less than 1 MeV of kinetic energy.

3.3 Collection

Figure 9 shows the energy distribution of positrons downstream of the target and their angular distribution. The main feature is that 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.

It is thus necessary to develop a positron collector in order to transport them efficiently at the trap entrance. In fact we will take advantage of this wide angle of production by using a system of coils producing diverging magnetic field lines at the location of the target.

3.4 Description of the setup

The x axis is the axis of the apparatus. The target is a thin rectangular tungsten plate of dimensions 2 cm x 2 cm x 50 μm. There are two possible ways to place the beam:

- setup 1: the beam axis coincides with the x axis, in which case the target plane makes a 3 degree angle with the x axis,
- setup 2: the beam axis x' makes an angle of 3 degrees with axis x, and the target plane contains the x axis.

The beam has the shape of a rectangular slit of 2 cm x 1 mm.

In the second configuration, a large part of the beam which traverses the target without much deflection separates from the x axis.

The collection system consists of two main coils of axis x (figure 10). The first coil, H_1, has a mean radius of 10 cm, a width along x of 5cm and a 5 Tesla field at its center. The target center is placed 20 cm downstream the center of H_1.

The second coil H_2 has a 30 cm radius, 20 kA.turns, producing in its center a 420 Gauss field in the same direction as the field at the center of H_1. It is placed 90 cm downstream of the center of the target.

A "recovery" tube consists of a series of flat coils of axis x in Helmholtz configuration one with respect to the next, each with a 10 cm diameter and 2 kA.turns. The first of these small coils is placed 10 cm downstream of H_2. The following ones are placed 7 cm from each other constituting a kind of open solenoid.

The beam goes through H_1 and hits the target. The particles exiting the target go then through H_2 and then through the recovery tube.

A small quadrupole of 10 cm internal radius is placed 11 cm downstream of the target. Its four coils have each a 3 cm radius and 2kA.turns, or a 250 Gauss field at their center. Two of its coils are vertical and the other two are horizontal. It pulls the positrons nearer to the x axis.

The field on the x axis at the center of the target is of 0.46 Tesla. The radial component at a radius of 1 cm from this axis is 0.28 Tesla.

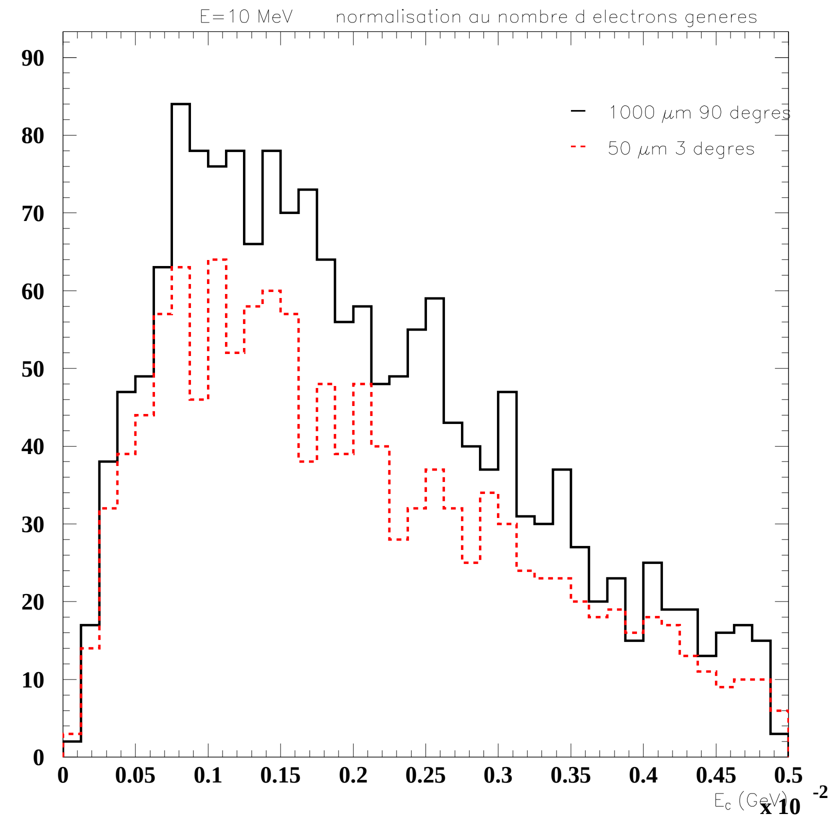
A dump made of tungsten of 1.6 cm diameter and 5 cm length is placed on the x axis at 51 cm downstream of the target.

In order to illuminate the target with a simple slit shaped electron beam, it is enough for setup 1 to include a tilt angle with respect to the vertical in order to correct for the deviation from coil H_1. For setup 2 a more complicated beam optics study must be performed.

3.5 Collection efficiency

Let us define the collection efficiency ϵ_5 (resp.ϵ_2) as the fraction of positrons of a given energy range reaching a plane perpendicular to the x axis and located inside the recovery tube at a distance of 2 m from the target, so 1.1 m after H_2, and whose intersection point with this plane is inside a circle of radius 5 cm (resp. 2 cm).

This efficiency depends on the transverse spread, with respect to the x axis, of the positron "beam spot". Figure 13 shows the efficiency variation with the radius of a hypothetical positron source located at the target position. For this calculation, we have generated a uniform spatial distribution of the emitted positrons inside a disk



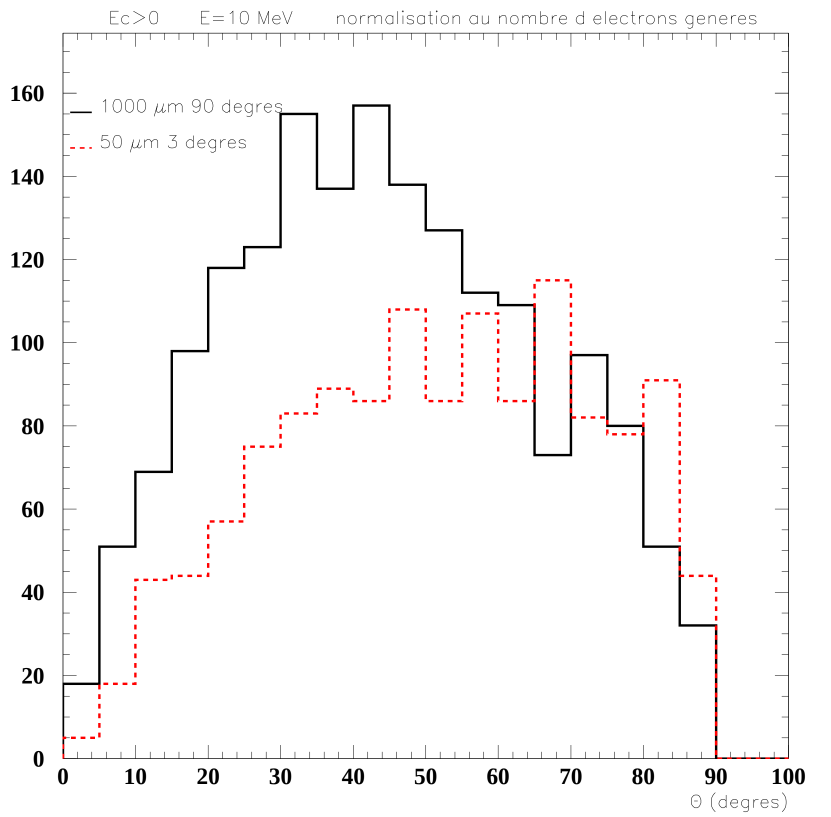


Figure 9: Spectra of the kinetic energy and production angle of positrons downstream of the target for 10^6 électrons with 3 and 90 degree incidence angles at a beam energy of 10 MeV. Distributions are normalized to the number of electrons generated. The maximum kinetic energy displayed is 5 MeV

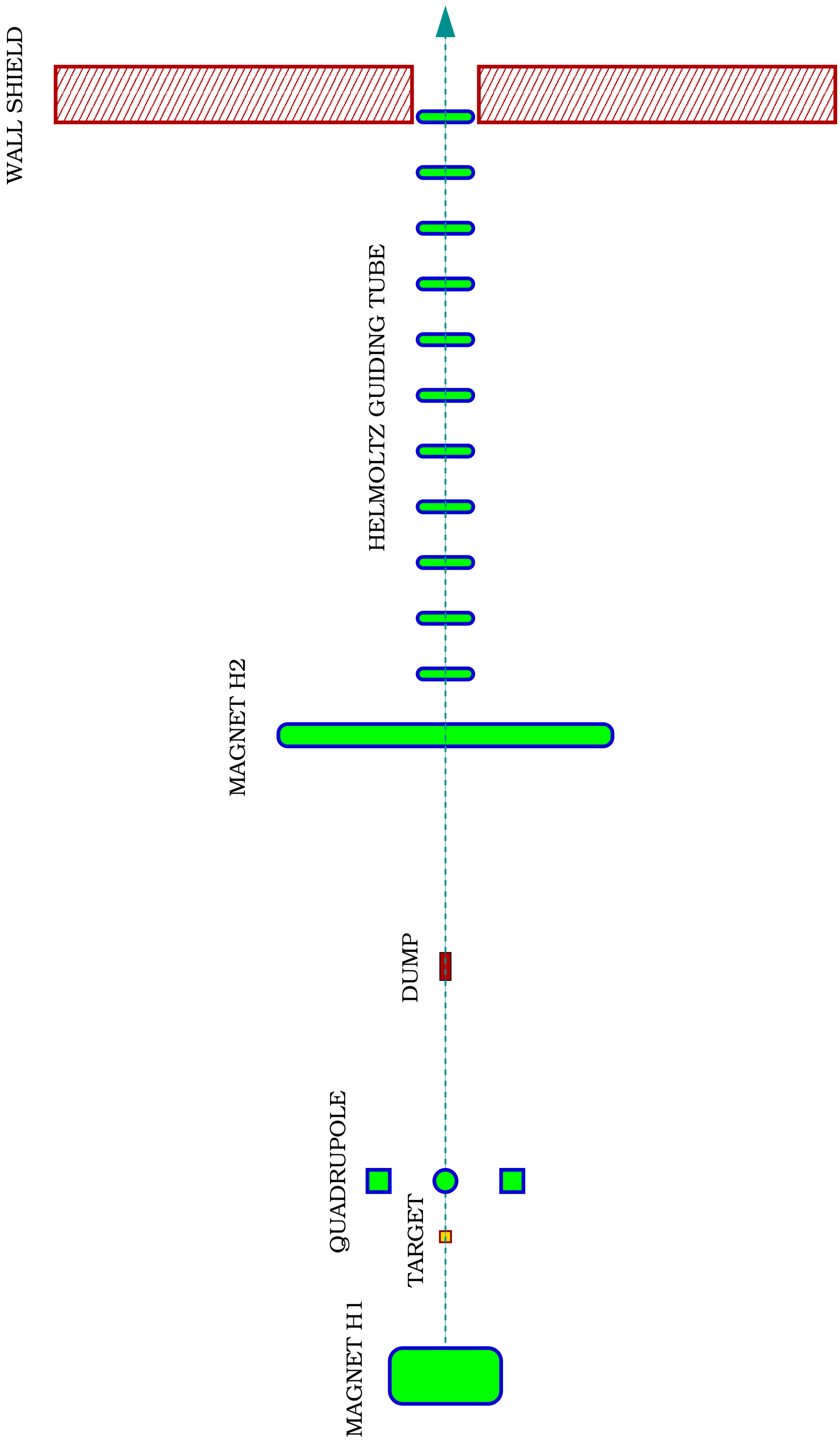


Figure 10: Layout of the proposed magnetic collection system.

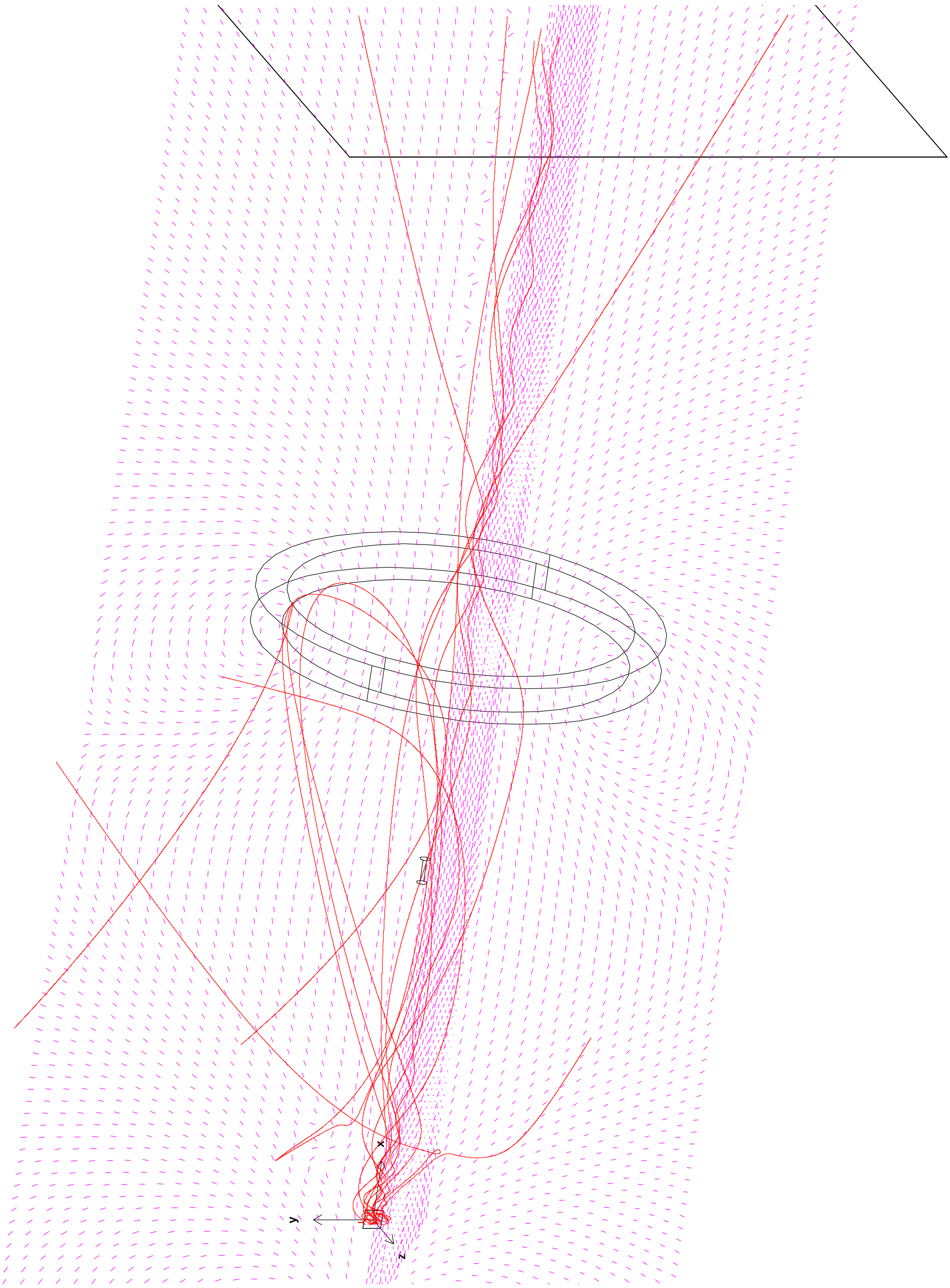


Figure 11: Positron tracks in the collection system: below 1 MeV the particles are guided to the exit tube.

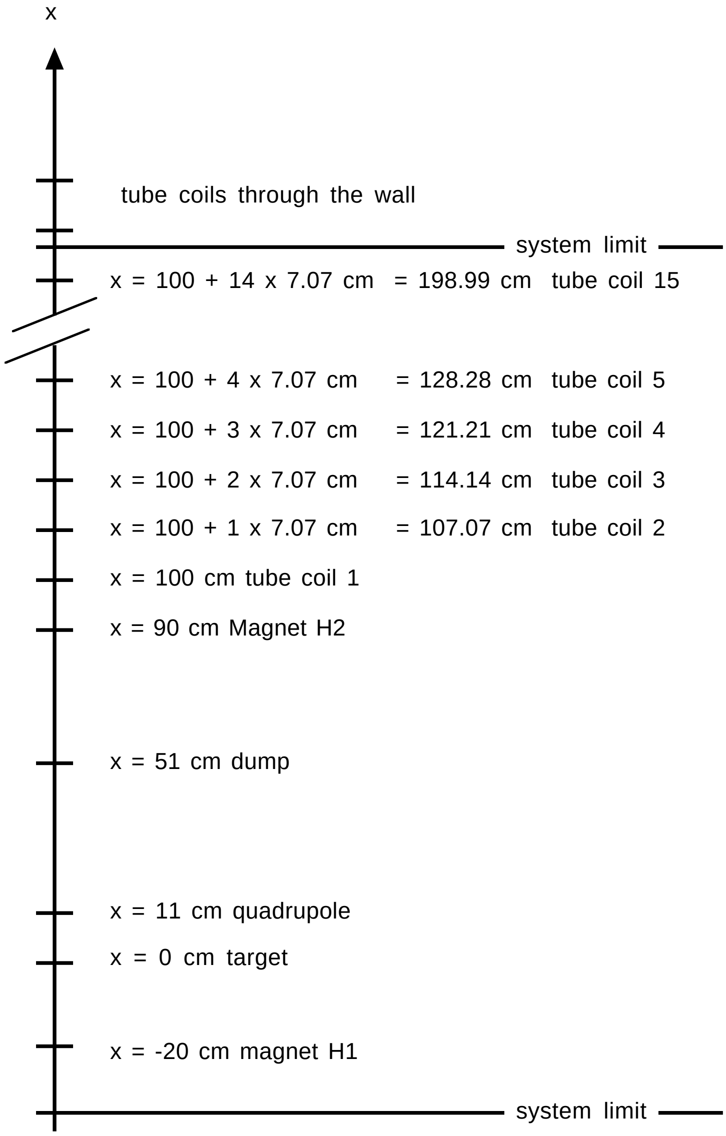


Figure 12: Layout scales

perpendicular to the x axis. The angular and energy spectrum corresponding to that of positrons exiting the tungsten target was kept. The efficiency decreases dramatically when the radius of this disk is increased.

On the same figure is also shown the efficiency obtained with a rectangular slit of 2 cm x 1 mm, the x axis being contained in the target plane, with or without correcting quadrupole. The same efficiency would be obtained with a disk shape if it had a radius of about 0.4 cm, which could only be obtained with a reduction of the surface of target illuminated by a factor of 0.13 with respect to the 4 cm^2 plate, and thus a reduction of about an order of magnitude in the rates.

Values for ϵ and the final rates of positrons at 2 m from the target are given in table 2.

Table 2: Collection efficiency and collection rates in units of $10^{12} s^{-1}$

$R_{coll} = 5cm$	ϵ_5	e^+ rate
Ec > 0	20%	4.2
Ec < 1 MeV	52%	2.7
Ec < 600 KeV	60%	1.3
$R_{coll} = 2cm$	ϵ_2	e^+ rate
Ec > 0	8%	1.6
Ec < 1 MeV	20%	1.1
Ec < 600 KeV	30%	0.6

3.6 Flux of electrons and photons

It is important to know the power coming from this device in the space downstream of the coils in order to design the room shielding, but also for the coupling to the trap which has a first stage at very low temperature.

Figures 17 and 18 show for setup 1 and 2 the flux of electrons and photons which cross planes perpendicular to the x axis, and whose intersection with these planes lie within circles of various radii, as a function of the distance between these planes and the target, for a 1 mA electron beam. The beam is supposed to illuminate the totality of the target surface. At target exit, 7.8 kW are collected. The power deposited in the target is 1.8 kW. The missing 400 W are back scattered.

The power reaching a plane located at 2.5 m from the target is given in detail in table 3 for an electron current of 2.3 mA.

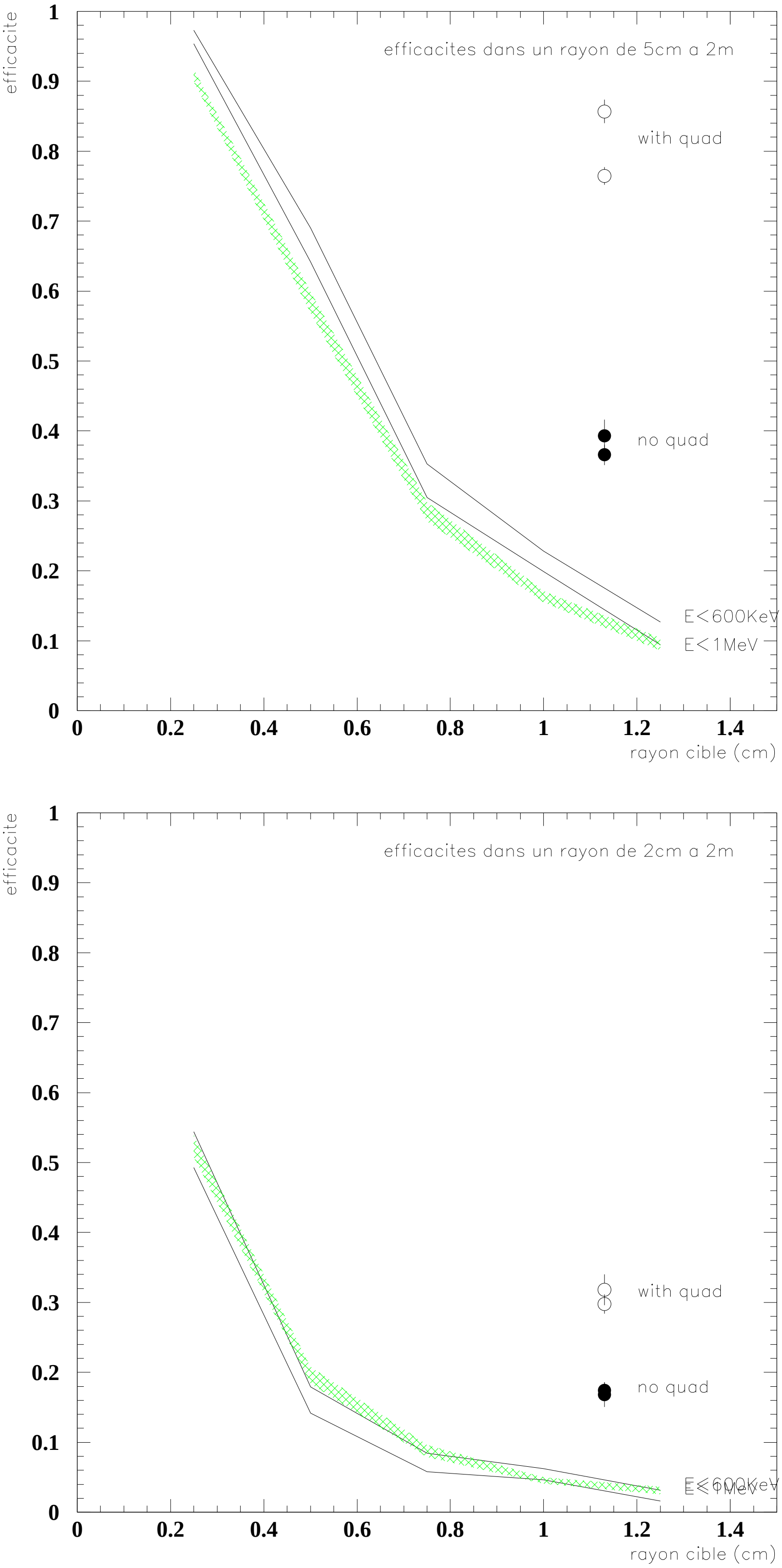


Figure 13: Efficiency as a function of the radius of a disk shaped beam for kinetic energies below 600 KeV. The hatched band corresponds to kinetic energies below 1 MeV. The points correspond to a 2 cm x 1 mm rectangular slit shaped beam parallel to the axis of the apparatus with or without correcting quadrupole. Top (resp. bottom) curves are for ϵ_5 (resp. ϵ_2)

Table 3: Power at 2.5 m from target as a function of radius, for 2.3 mA.

	R = 1 cm	R = 2 cm	R = 3 cm	R = 4 cm
setup 1	5 W	140 W	450 W	1.5 kW
setup 2	10 W	45 W	80 W	110 W

3.7 Source Output Measurement

The performances of this source must be demonstrated prior to commissioning for use with the trap by measuring the e^+ flux at its output. In this section, we describe the principles of possible ways to measure this flux.

This measurement can be performed by inserting a dipole after the exit wall, with its center field in the vertical direction. The magnetic field bends the trajectories of electrons on one side and the positrons on the other side where they are detected.

An alternative method has been studied which replaces the magnetic field with a 2 μm thick single moderator tungsten foil. It has lateral dimensions of 5 cm x 5 cm and intercepts the output particles at 2.3 m from the target. The moderated positrons are extracted by applying a weak electric field in order to direct them towards the detector.

The detector is 3 cm in diameter and consists of an Aluminium converter and a pure CsI crystal equipped with a photomultiplier. This detector is shielded with a 10 cm thick lead cover. A schematic view is shown in figure 14.

We simulate with GEANT 10^8 incident electrons on target. After propagation through the collector we record the electrons and positrons 1.9 m downstream from the target in order to estimate the system efficiency.

Each 10 MeV electron on target gives 2 10^{-4} electron at the exit tube and 3 10^{-6} positron. The ratio of positrons to electrons after the collector is 1.5% while each 10 MeV electron produces only 2 10^{-4} positron of less than 1 MeV. Furthermore, as shown in the previous sections, this rejection of electrons is obtained while preserving the low energy part of the positron spectrum.

The 2D distribution of energy versus angle (w.r.t. x axis) of electrons and positrons exiting the tube, is used to make a Monte Carlo generator at 190 cm, after the target and collector. With this generator we simulate, at the exit tube, the equivalent of 1.2 10^{11} electrons on target. This generator is used to estimate the signal for both methods, the magnetic dipole and the moderator foil.

In the simulation of the first type of measurement, a pair of Helmoltz coils is placed at the tube exit to form a magnetic dipole. Its axis is vertical and its center is at 2.3 m from the target on the apparatus axis (x=230 cm, y=0 cm, z=0 cm). The coils have a diameter of 20 cm and a spacing of 25 cm, with 10000 At. The Al converter is 4 mm thick. The counting rate is such that a fast (100 ns integration time) counter is needed with 10% resolution at 511 KeV.

A 0.25 mA beam intensity, i.e. $1.610^{15}e^-/s$, makes on average 1.6 $10^8 e^-$ on target during a 100 ns integration gate. We generated the equivalent of 400 such gates and observe no hit at detector level within 10% of the 511 KeV line in the run with e^- and 25 hits in the e^+ run.

The second type of measurement is a simplification of a possible setup with a buffer gas trap. The Neon moderator being replaced by the tungsten foil, and the trap itself is replaced by the NaI detector. Such a setup needs more study as we do not have a simulation of the moderation process. However if we take a value of 10^{-4} for the moderation efficiency, a 100μm thick Al converter, and a set of coils to guide positrons, we estimate a S/B ratio of 3.

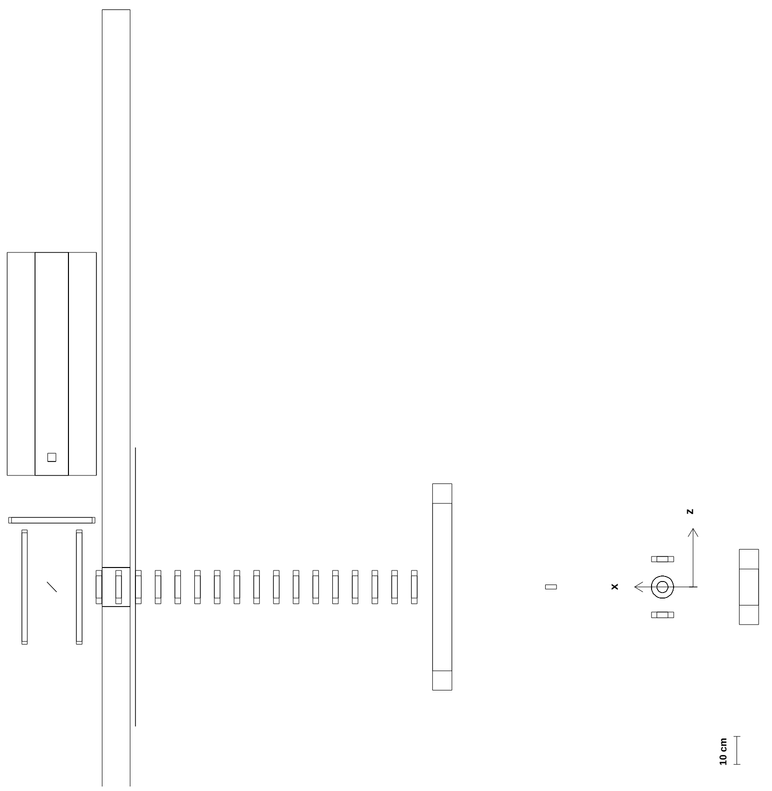


Figure 14: Source output measurement: setup with moderator foil

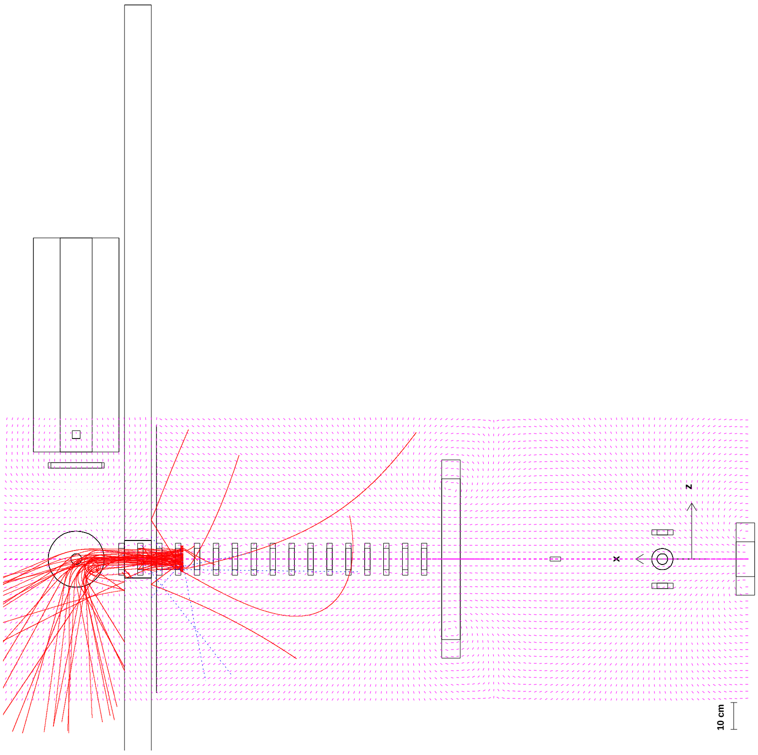


Figure 15: Source output measurement: setup with dipole and electrons

3.8 Summary

A system of production and collection of MeV positrons has been presented. This setup uses pair creation from electrons hitting a thin tungsten target at a 3 degree incidence angle. The beam comes from a 10 MeV/2.3 mA electron accelerator running in continuous mode. The setup allows to collect more than 5 $10^{11} s^{-1}$ positrons of less than 600 keV in a 2 cm radius aperture at 2 m from the target. The flux of electrons and photons reaching this aperture is of the order of 100 W.

The system is designed to adapt to a Greaves-Surko trap.

4 Competition

There are three classes of positron production techniques: classical β^+ radioactive sources, *in situ* production of short lived β^+ sources, pair production with a linac or via a nuclear reaction.

The β^+ sources produce a positron current which is limited by the thickness of the embedding material. One gets currently 100 mCi ^{22}Na sources which produce some 10^8e$^+$/s, i.e. after moderation order of 10^6e$^+$/s. The mean lifetime is 2.6 years. The

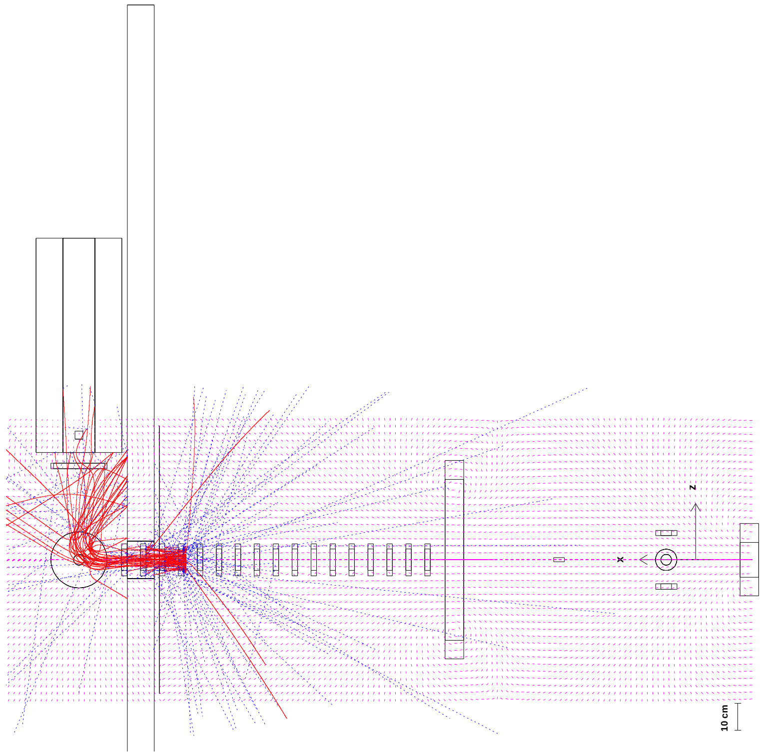


Figure 16: Source output measurement: setup with dipole and positrons

price is about 100k USD.

The Paul Scherrer Institute (PSI) has a ^{58}Co source of 500 mCi. A project comprises a one Tesla superconducting magnet and 200kV electrodes. In this magnetic bottle, the energy of the positrons is dissipated in a thin carbon blade. Positrons are thus slowed down to 3 KeV with small losses. This low energy is best adapted to the moderator and would give a gain of a factor 200 on moderation efficiency. The potential of this installation is of 10^{10} slow positrons per second [23].

Another solution consists in irradiating copper with neutrons from a nuclear reactor. The High Flux Beam Reactor in BNL obtained 100 Curies of ^{64}Cu (T=12.8h) before its stop. However the current varied quickly with time with a maximum of 10^7 slow e^+ per second. Delft University might use this technique again on its new experimental reactor.

Brandeis University proposes a beam of deuterons of 1.5 MeV on carbon which produces ^{13}N (T=9.97 min). This idea could achieve 10^7 positrons per second.

In Garching, near Munich, the research reactor FRM-II will be used via neutron capture on cadmium, $^{113}Cd(n,\gamma)^{114}Cd$, to produce a flux of order 10^{10} slow positrons per second [24].

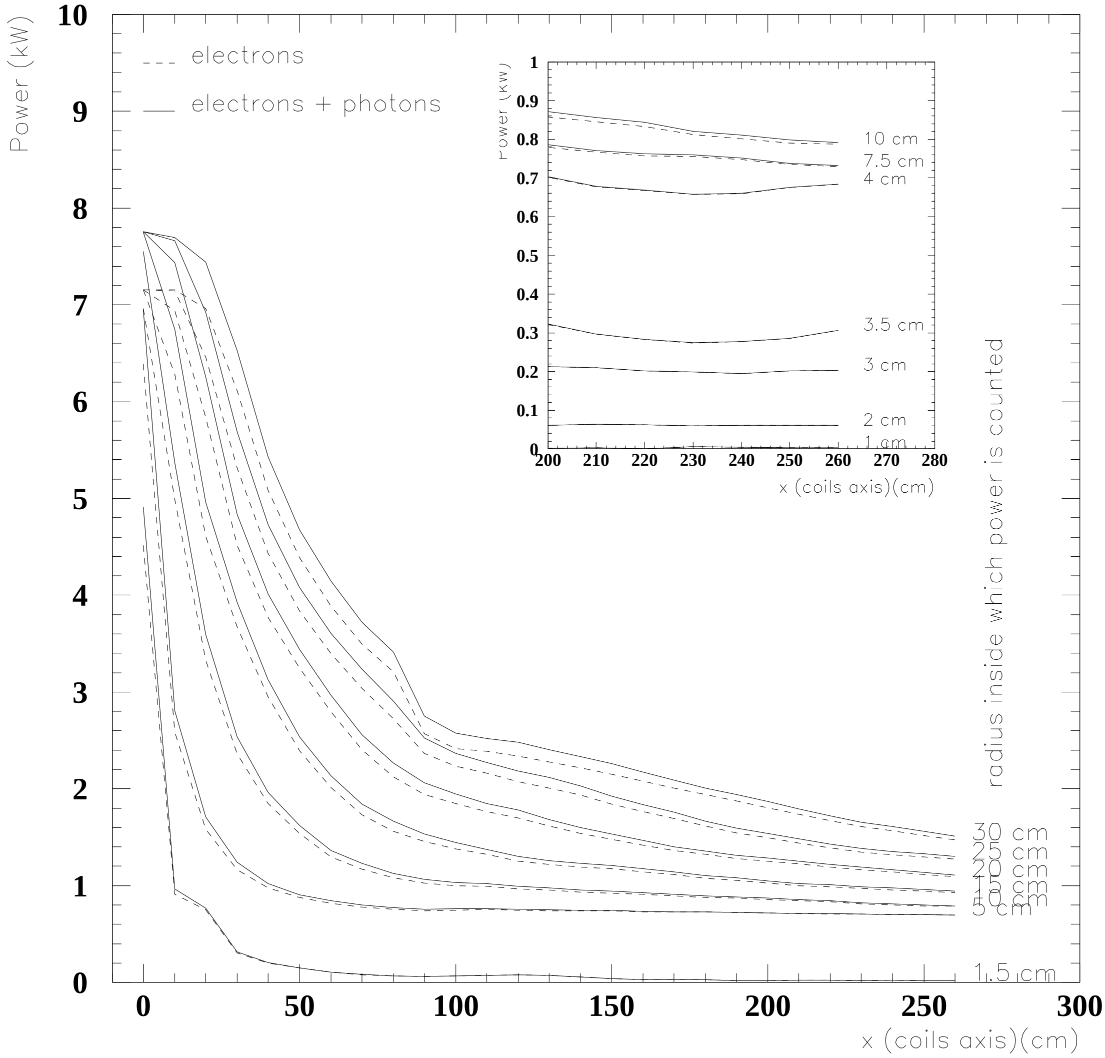


Figure 17: **Setup 1**. Flux of electrons and photons (full line) and electrons (dashed line) within circular sectors around the setup axis as a function of the distance to the target for several radii of the circular sectors. The total beam power is 10 kW.

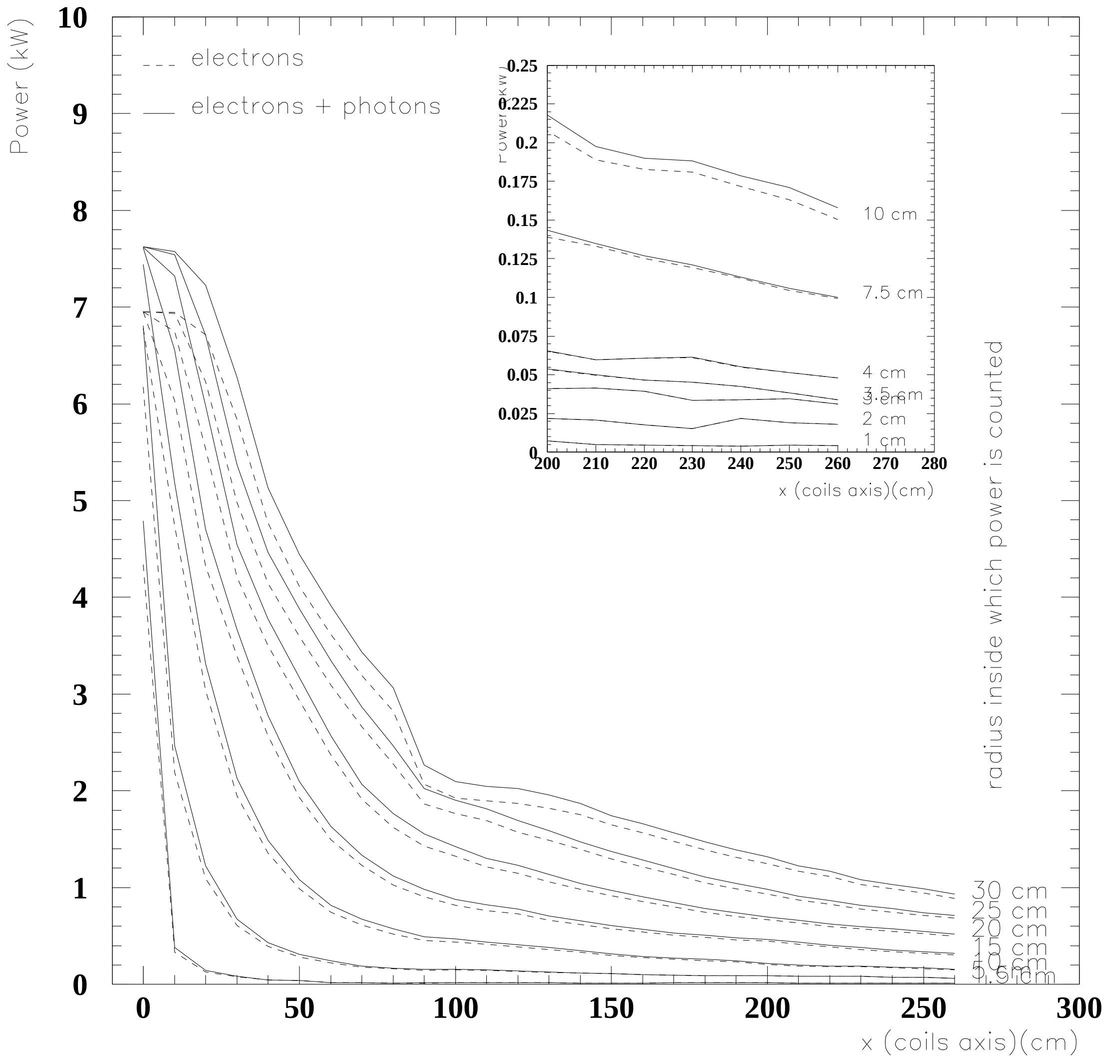


Figure 18: **Setup 2**. Flux of electrons and photons (full line) and electrons (dashed line) within circular sectors around the setup axis as a function of the distance to the target for several radii of the circular sectors. The total beam power is 10 kW.

A patent is being filed on a concept based on a tandem accelerator of 1mA with protons of 2 MeV. Protons hit SF_6, which produces a ^{16}O state which decays in 70 fs to produce an electron and a positron which share a kinetic energy of 6.05 MeV. After the necessary moderation the expected rate is 10^7 to 10^8 slow positrons per second [25]. This project named EPITRON® has the advantage, according to the authors, to be compact in terms of operation and power, cheap at buying and operation, does not induce radioactivity and is changeable in its applications.

The other main way to produce positrons uses linacs. The target is tungsten, tantalum or platinum. Several kinds of arrangements exist of sheets of moderating material from which slow positrons are extracted. Let us cite the most well known laboratories:

Lawrence Livermore (LLNL) which has a 100MeV linac of 45kW, with a dedicated extraction providing 10^{10} positrons per second [26]. The ORELA complex located in Oak Ridge consists of a linac of 180 MeV and 60 kW which produces 10^8 slow positrons per second. There is also a High Flux Positron Beam in BNL.

In Japan, the National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba, is building an "Intense Slow Positron Beam Facility" with a 70MeV linac in order to produce 10^8 slow positrons per second. In KEK, the new positron facility is based on a 25 MeV/1kW linac which should produce the same rate of positrons. In Germany, in Halle University, the EPOS complex is based on a 40 MeV/40 kW linac which is expected to deliver a flux of 8.5 10^8 slow positrons per second [27].

Finally let us cite the possibility to insert an undulator in a GeV electron beam which would lead to the production of $10^{13}e^+s^{-1}$ in the MeV range at very high brightness [28]. However this idea is not yet a project and would be fixed with an important complex.

The large linac installations are too few to be favorable places for the development of applications. An installation like PF1 at the ILL of Grenoble which served as a test for FRM-II is also not intended to be generalized. The present tendency is to build small facilities of the size of a university laboratory or of a small business firm. Other projects are surely being studied.

5 Proposal

The foreseen source is of the same type as a synchrotron radiation facility, but smaller and operated in time sharing mode between several small experiments open to both fundamental research and applied physics. The scope of this proposal is limited to the construction and testing of the source; experiments will be subject to separate applications. The time frame is 3 years from the acceptance to get the e^+ source.

The source itself is made of two sections:
- the 10 MeV accelerator with a dump
- the target and collector system

Then, after joining with the UC San Diego group, it will take one year to get the facility operational by adding the moderator, buffer gas and trap system.

The best electron source for this application is a Rhodotron, which is commercialized by the IBA [20] firm. This compact machine (about 3 m in diameter) is operated continuously all year long and can reach beam intensities up to 100 mA for food disinfection. Several models are available according to the desired beam intensity. It has a very good efficiency: a 10 MeV/2mA model would use only 50 kW of power. The cost of such a machine is approximatively 2.5M USD.

Alternatively, we may consider a high intensity 10 MeV linac such as the one assembled and sold by TitanScan Technologies [29] in San Diego for medical items disinfection. This machine provides a beam with an intensity of 1.8 mA and is operated 7400 hours/year. All the components (gun, klystron, accelerating structure) are commercial products with only one component developed by TitanScan. This component is a monitor and control system which prevents beam intensity excursions and has allowed the operation of the machine for 5 years without having to replace a component. The cost of the components to assemble such a linac, including the monitor and control system but without the power supply is approximatively 300 k USD. The power required is 160 kW.

The two systems having the same size, about 3 meter, and the same shielding requirements, we propose to develop the positron source with the cheapest system, the linac, and to keep open the possibility to replace it in the future with a Rhodotron.

The second section (target system and collector) is being engineered by CEA-Saclay. A very preliminary cost estimate amounts to 150 K euros. In parallel some tests on target evaporation will be performed with the help of IBA.

The last section (trap) is being developed by an ongoing program at UC San Diego and is expected to reach a cooling and storing capacity in the range $10^{12} - 10^{13}$ positrons within 3 to 4 years. The budget to replicate such a trap and install it at SLAC, not including the moderation step, is around 500 K USD. This team will join our effort when new funding is secured for the replication at SLAC, and this section will be installed and tested at the exit of the collector system. Our proposal was designed in accordance with this ongoing development.

The investment and running costs of such a project are dominated by the building which can host an intense 10 MeV source. It is of the order of 50 % of the total cost (about 2.5M USD). When industrialized, nobody enters such a building (only the objects to be disinfected do). In the present project the users enter the building in order to install their experiment (3d picture of a molecule or laser experiment, etc...). Therefore there is a need for the security and medical checking infrastructure (film badges etc...).

The SLAC site is ideal to host this project for the following reasons:

- SLAC is an interdisciplinary laboratory with a unique mixture of HEP, Synchrotron radiation and Linac experts community. The recent creation of the Kavli institute will benefit from the positron experimental program in the field of plasma physics and gravitation.

- the transformation of an existing HEP experimental area or of an existing HEP building to accomodate the source could divide the investment cost by a factor two.

- the radiation control infrastructure already exists at SLAC both for HEP and synchrotron radiation.

- the San Diego team will have to move their apparatus and then operate it to capture, cool and store the e^+: the nearest place with the proper infrastructure is SLAC.

- the firms that provide the pieces for the 10 MeV intense linac are all within 50 miles of SLAC.

- the company that builds the buffer gas for the e^+ is also in california [16].

SLAC has both a HEP community and a Synchrotron light facility users community (SSRL). What we propose is an interdisciplinary facility. On top of security and medical infrastructure, the technical surrounding and know how in electron accelerators is also required to help us reach the beam intensity and reliability of operation over long periods. In short, SLAC has the right location for our partners from San Diego, the right infrastructure, the right community of users and the right technical and scientific expertise.

Gravitation is the only fondamental interaction for which experimental data with single elementary neutral particles are very scarce and data with antimatter non existant. Experiments have been made with multi-electron atoms in atomic fountains and with thermal neutrons from a nuclear reactor. But the free fall of a single hydrogen atom, triggered at will, has never been measured. The free fall of Positronium atoms has never been observed. These are the first two experiments in particle physics that this facility will allow. Furthermore the production of hydrogen and anti-hydrogen is fully symmetric in this apparatus: once the experiment with hydrogen is operational, the replacement of protons with antiprotons from a trap will allow the first observation of the gravitation interaction on antimatter with a single neutral atom.

6 Request to the SLAC EPAC

With this presentation, we request the EPAC to comment on the physics goals, recognizing the interdisciplinarity of the project and the ideal capabilities and expertise SLAC offers; to encourage the development of a full technical proposal and to encourage a SLAC workshop to take place this winter.

This workshop would be aimed at defining the technical aspects and physics capabilities from the point of view of the potential users. It would be the opportunity to start a users community of the positron source and to answer practical questions such as the size of the foreseen experiments, the data taking time scheduling, the level of radiation shielding required, etc...

It would also be the opportunity to discuss with the users the minimal expected operation time of the facility. This operation time and a view on the future of such an apparatus after the first set of experiments seems to us important to assert wether it is worth the financial investment.

Acknowledgements

In order to design this project we had fruitful discussions with several people from different fields who all gave some time to answer our questions. We also were able to use the RADIOLYSE facility at Saclay and the electron beam welding facility at the LAL-orsay. At SLAC and at the University of San Diego our colleagues organized meetings for us to meet the experts and discuss the scientific interest. In Saclay, the fact that several laboratories are part of the same department, the CEA/DSM, gave us the possibility to interact simultaneously with engineers and physicists for questions of coil design, cryogenics, antimatter physics, plasma physics, thermal problems and many other points for which the direct exchange with the expert is essential. We wish to express our sincere thanks to all these people, listed below and grouped by institutions.

CEA Saclay: *B. Aune, G. Baldacchino, G. Chardin, G. Cozzika, P. Debu, M. Jablonka, M. Jacquemet, J.C. Languillat, D. Lestelle, J.P. Lottin, B. Mansoulié, J. Mallet, F. Méot, J.C. Mialocq, A. N'Guyen, F. Nunio, S. Pommeret, J.M. Rifflet, M. Spiro, G. Vigneron*

LAL Orsay: *P. Lecoeur, J.L Borne*

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University of San Diego: *C. Surko*

First Point Scientific, Inc., Agoura Hills: *R. Greaves*

University of Riverside: *A.P. Mills*

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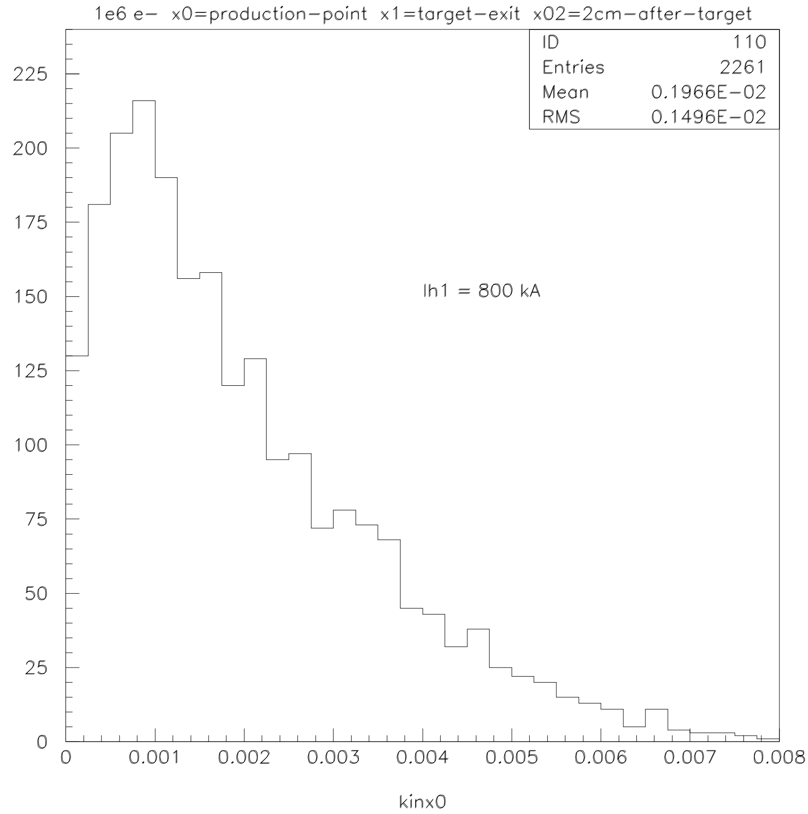

Figure 19: Kinetic energy of the positrons at the creation point inside the target (GeV)

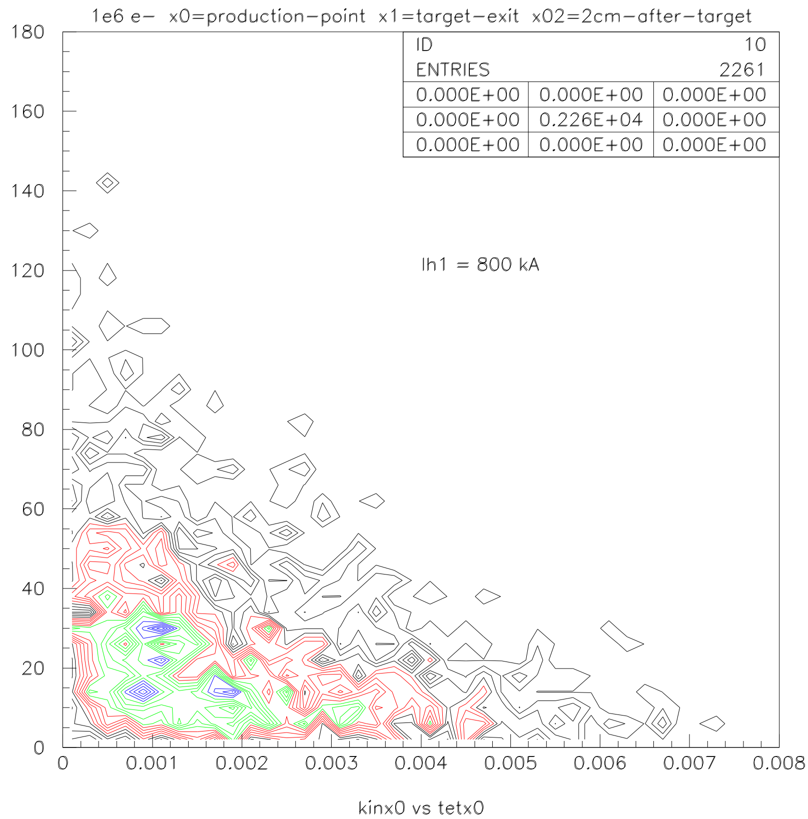

Figure 20: Kinetic energy versus polar angle of the positrons a the creation point inside the target (GeV, degrees)

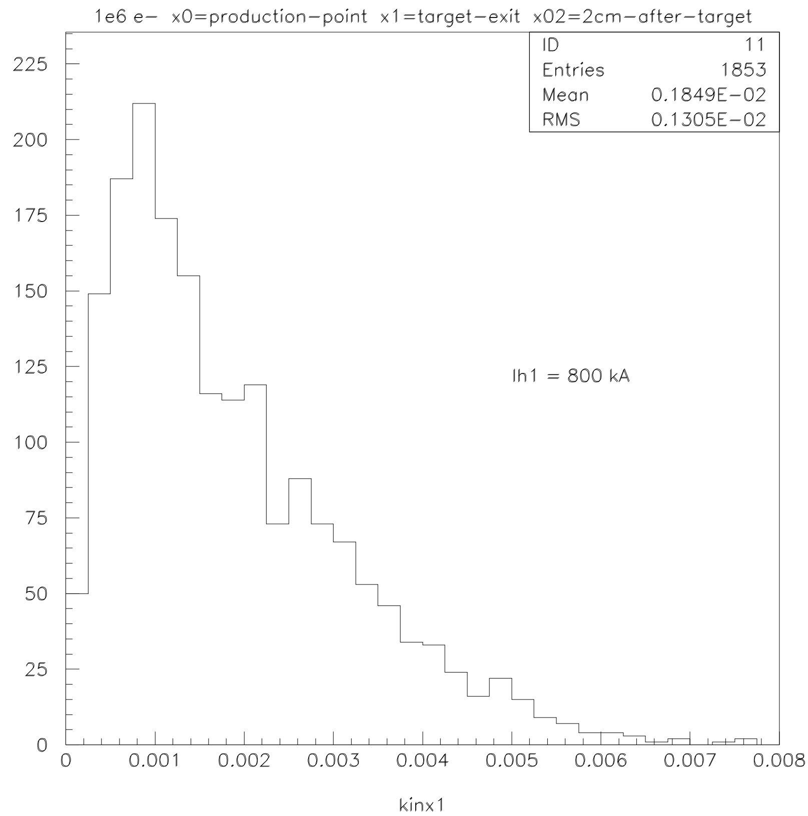

Figure 21: Kinetic energy of the positrons after leaving the target (GeV)

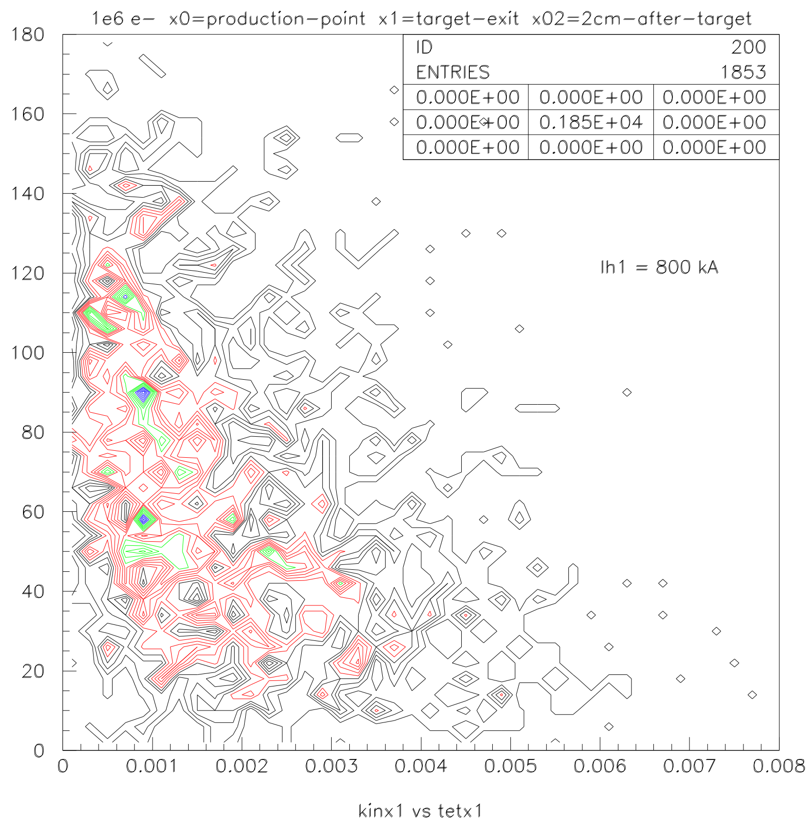

Figure 22: Kinetic energy versus polar angle of the positrons after leaving the target (GeV , degrees)

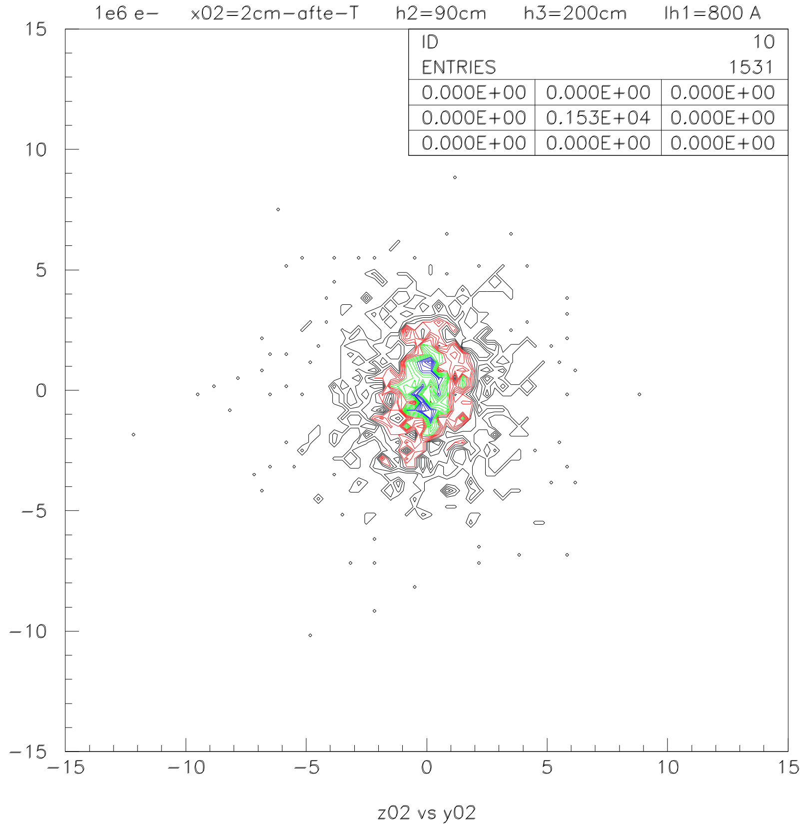

Figure 23: Position of the positrons in the plane orthogonal to the system axis at x=2cm (cm , cm)

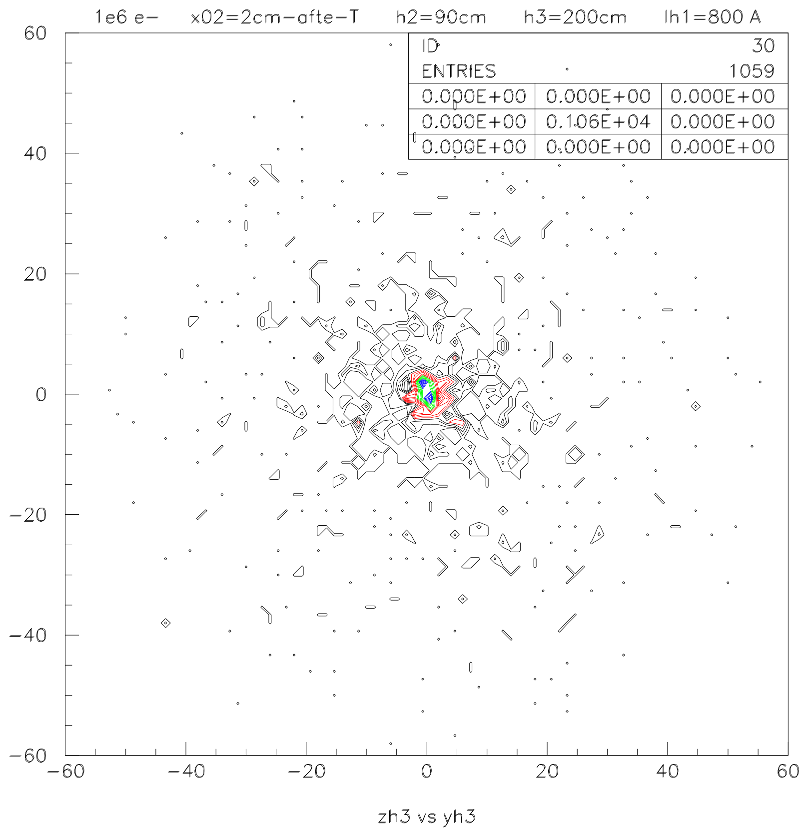

Figure 24: Position of the positrons in the plane orthogonal to the system axis at x=200cm (cm , cm)

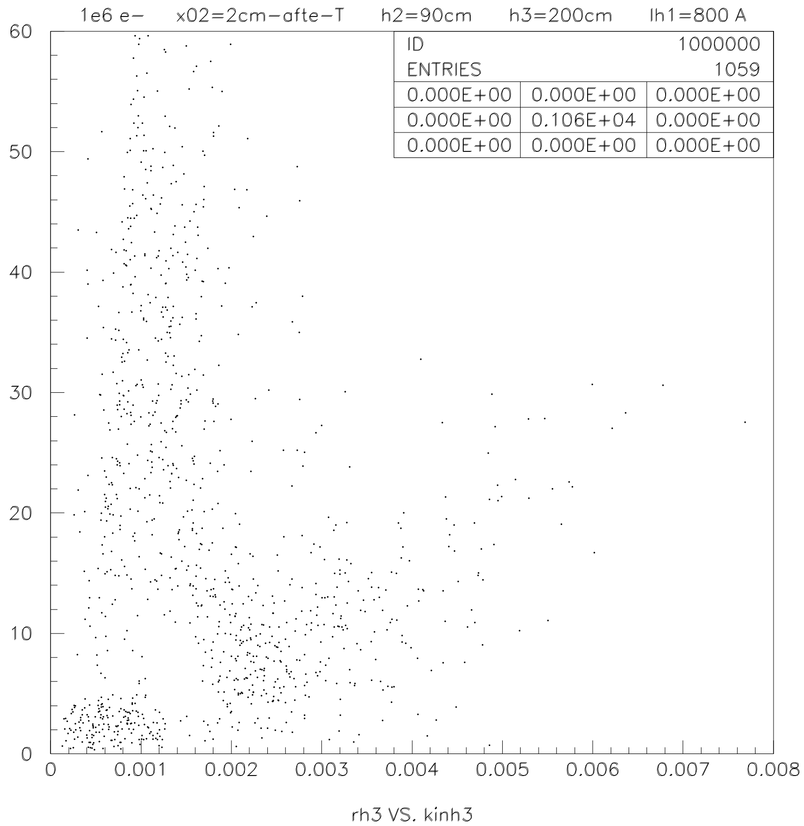

Figure 25: Kinetic energy versus radial position of the positrons in the plane orthogonal to the system axis at x=200cm (GeV , cm)

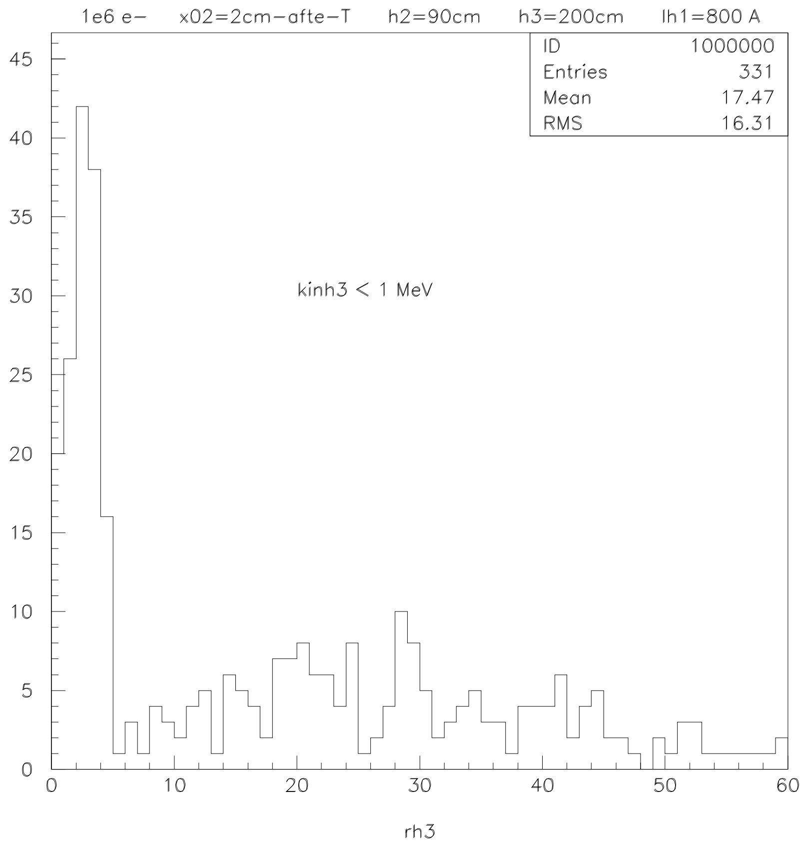

Figure 26: Radial position of the positrons in the plane orthogonal to the system axis at x=200cm (cm)

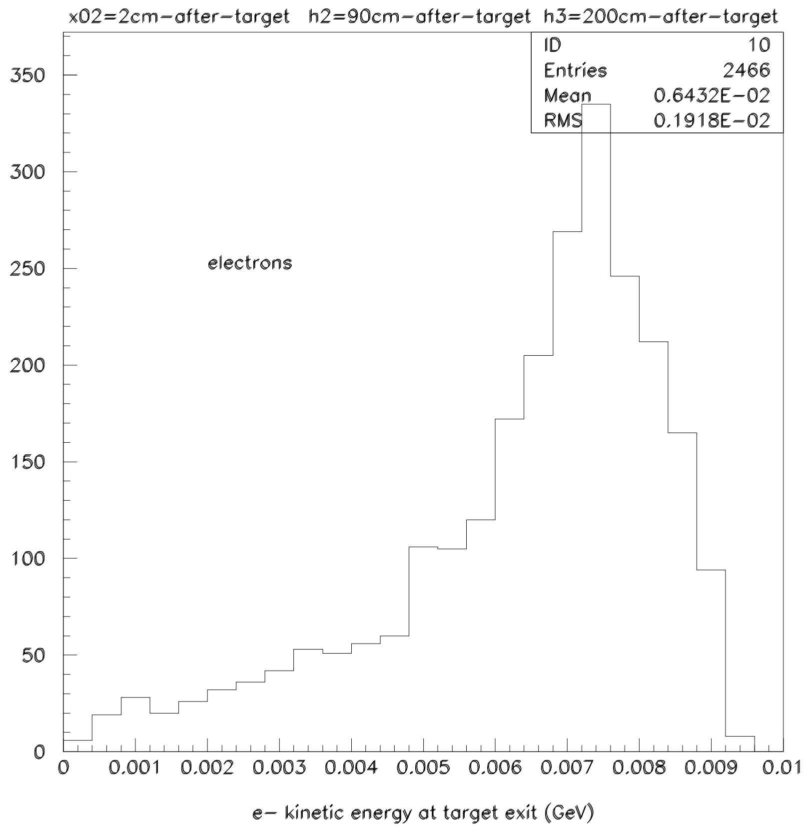

Figure 27: Kinetic energy of the electrons after leaving the target (GeV)

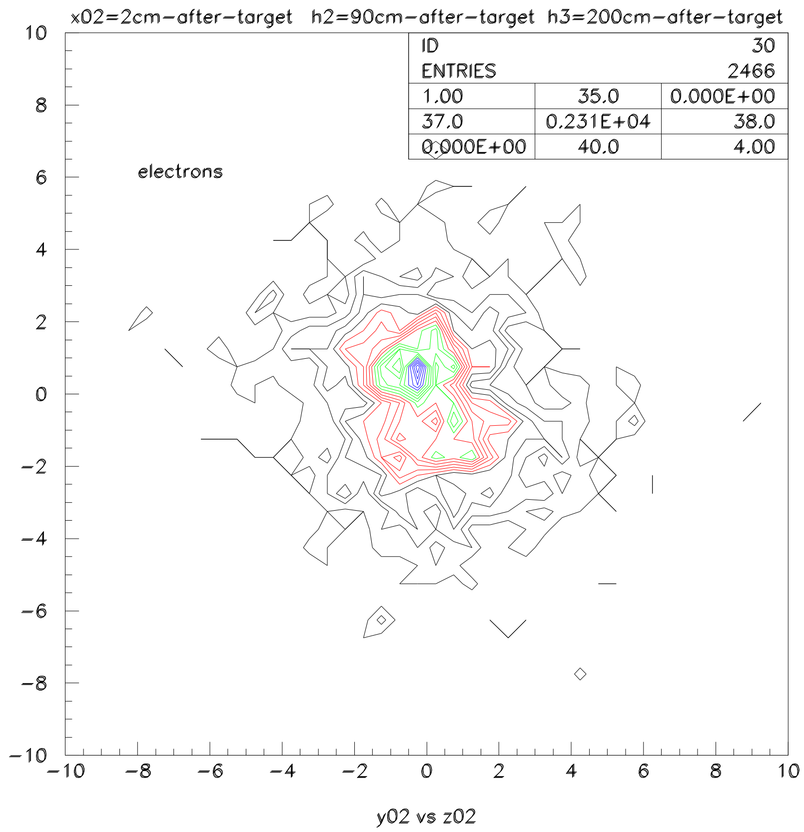

Figure 28: Position of the electrons in the plane orthogonal to the system axis at x=2cm (cm , cm)

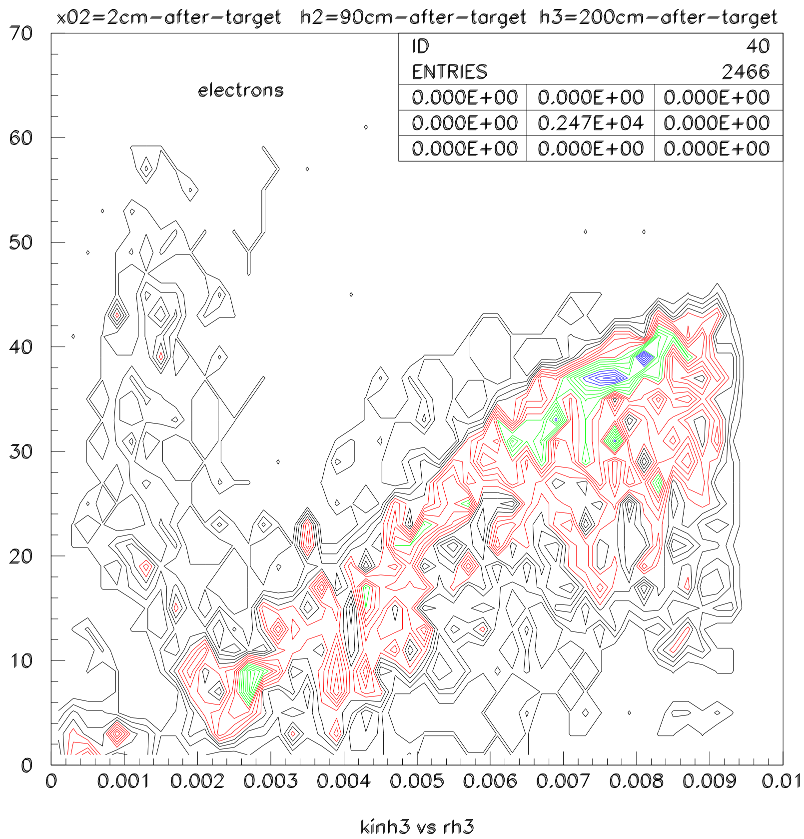

Figure 29: Kinetic energy versus radial position of the electrons in the plane orthogonal to the system axis at x=200cm (GeV , cm)

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October 6, 2003

To: Patrice Perez and Andre Rosowsky

From: Cliff Surko

Re: Potential utility of an intense positron source

The following is my perspective on the great utility that an intense source of slow positrons at SLAC would provide to the scientific community. As an introduction, phenomena involving positrons are important in many fields of physics, including astrophysics [1], plasma physics [2-6] atomic physics [7-9], and materials science [10].[*] In the laboratory, low-energy positrons are now being used for many of these applications, including study of electron-positron plasma phenomena [3, 4], atomic and molecular physics [7, 8], antihydrogen formation [11-14], modeling of astrophysical processes [15], and the characterization of materials [10]. This list of uses is growing rapidly.

Laboratory study of phenomena involving positrons has clearly been limited by the relative unavailability of suitable positron sources and the inability to manipulate these collections of antimatter. So there are two issues, suitable sources of slow positrons and methods to accumulate, cool and manipulate positron plasmas.

I. Need for a high-flux positron facility.

Present-day buffer gas positron traps, such as those described below, have the potential to trap and cool positrons at a rate approaching 10^9 s^{-1}. Thus, assuming a trapping efficiency ~ 0.3, ***currently available positron traps could immediately utilize slow positron fluxes of 3 x*** 10^9 s^{-1}. Multiplexing users is quite feasible so that fluxes in excess of 10^{10} s^{-1} would be of immediate utility. In contrast, radioisotope sources currently in use provide fluxes ≤ 2 x 10^7 s^{-1}. ***Thus the gap between what one could utilize and what is currently available from radioisotope sources differs by a factor ~*** 10^2 - 10^3. ***A slow positron source with flux ≥*** 10^9 e^+ s^{-1} ***would be extremely useful in a range of applications.***

II. Potential uses of high-flux positron sources.

There are many potential uses of such a facility. Following are some examples:

Electron-positron plasmas. Electron-positron plasmas are unique, exhibiting a variety of novel behavior such as linearly polarized cyclotron radiation and nonlinear plasma processes dramatically different than in electron/ion plasmas (e.g., the absence of three-wave coupling and nonlinear Landau damping larger by the electron/ion mass ratio, M/m) [2]. Relativistic electron-positron plasmas are important special class of plasmas that are relevant to astrophysical settings

[*] Numerous references are included, since some readers of this memo might not be intimately familiar with specific aspects of the science and technology described here and would like to learn more.

such as the magnetospheres of pulsars [16]. While electron-positron plasmas have been considered extensively in theoretical and computational work, due to the lack of suitable positron sources, laboratory experiments have been limited to a beam-plasma geometry [4, 17]. Plasma confinement devices such as stellerators are currently being developed that are specifically designed to confine and study of "neutral" electron-positron plasmas [5]. However, in order to use these devices, one must accommodate significant fluxes of positron transport out of the plasma (e.g., confinement times ~ milliseconds to seconds) [18]. Current radioisotope sources are marginal at best for these studies and so an intense positron source is very important for these studies..

Relativisitic electron-positron plasmas, which are of interest because of their importance in astrophysical contexts, are even more challenging to study, since at higher temperatures, the Debye screening length is much larger. In this case, to enter the plasma regime even with a mildly relativistic plasma, one must work with larger plasmas and higher plasma densities, thus requiring many more positrons (e.g., positron numbers, $N \sim 10^{14}$). Such a plasma could be confined in a magnetic mirror device, with the plasma heated using microwaves [18]. While such relativistic plasmas could possibly be produced for very short time periods using intense laser beams, a more conventional approach using a high-flux positron facility would be of enormous benefit to this area of science. This would permit study of the underlying plasma phenomena on a much longer time scale (e.g., $\geq 10^{-3} - 1$ sec.) and hence with more precision.

Cold, bright positron beams. Positrons have been used extensively to study materials [10]. One important example is characterizing low dielectric constant insulators that are key components in high-speed electronics and chip manufacture. Positron annihilation lifetime studies (PALS) is the method of choice for these studies [19]. An important focus of recent work in the materials area has been the development of pulsed, trap based positron beams that now offer new ways to make a variety of measurements [20]. A high-flux positron facility would offer important new capabilities in areas such as positron microscopy and other spatially resolved material probes using positrons.

Giant pulses of positrons. There is much interest in studying the many-body electron-positron system at high densities [21]. The first goal is observation of the positronium molecule, Ps_2 [22]. Other more ambitious goals include creating a Ps BEC [23] and ultimately, creating an annihilation gamma-ray laser [22]. This exciting experimental direction would benefit greatly from an intense positron source.

Portable positron sources. One long-term goal in antimatter science is the development of portable antimatter traps. In the case of positrons, portable traps would enable experiments in settings where use of radioisotope sources are either impractical or inconvenient (e.g., to characterize materials at a chip manufacturing facility). As described below, we are currently in the conceptual design stage for such a portable trap. Our current estimate is that a portable trap for $N \sim 10^{12}$ positrons would be of considerable commercial utility as a cost-effective alternative to conventional radioisotope positron sources currently in use. These portable traps will require a a high-flux source of positrons for filling and refilling.

III. Tools to create, cool and manipulate positron plasmas.

Here at UCSD, we are continuing to develop new methods to create, confine and manipulate positron plasmas and beams. Many of these techniques would be useful at an intense positron facility. In the following paragraphs, I present a brief overview of this work. We developed a method to accumulate positrons in a specially designed Penning-Malmberg trap using inelastic collisions with a suitably chosen molecular buffer gas [3, 24, 25]. It is the most efficient antimatter accumulation technique developed to date [25]. This device is now used in a number of laboratories around the World, produced for sale commercially [26], and [11] in one of two recent experiments that created the first low-energy antihydrogen atoms at CERN [11-13].

The buffer-gas accumulator was used, in turn, to develop a new method to create cold, bright positron beams [27, 28]. These beams have advanced the state of the art in energy resolution by more than an order of magnitude. They have provided new opportunities to study the interaction of positrons with ordinary matter, exploring basic aspects of plasma physics and atomic and molecular physics [4, 17, 29-32]. This positron beam work also led to the development of a commercial-prototype positron beam source to characterize materials [33].

The rotating electric field technique to radially compress single-component plasmas has provided an immensely useful tool for positron research. Developed recently to confine and compress electron and ion plasmas [34-36], our group achieved a compression factor of 20 in plasma density in the first application of the technique to positron plasmas. [37, 38]. This technique can be used to achieve very long confinement times, increase plasma density, and brightness-enhance trap-based positron beams.

We are now undertaking research to utilize a recently constructed device that is designed to create high-density, cryogenic positron plasmas (e.g., $T \leq 10$ kelvin), in a UHV environment and cooled by cyclotron radiation. This trap is expected to provide a nearly ideal device for the long-term storage of antimatter. Objectives include the confinement of large numbers of positrons ($N > 10^{10}$) for very long confinement and annihilation times (e.g., days). This cryogenic trap will also be used to create a new generation of cold, bright positron beams (i.e., temperatures ~ 1 meV ≅ 10 K). Finally, we plan to use the resulting plasma states in the development of a novel multicell trap [39] that has the potential to increase trapping capacity by additional orders of magnitude. This multicell trap design could provide the basis for a practical portable positron trap described above.

I also note that there is complementary activity here in Southern California by my colleague and collaborator Dr. Roderick Greaves from First Point Scientific, Inc., Agoura Hills, CA. Dr. Greaves is building buffer-gas positron traps for sale commercially and is developing commercial prototype trap-based positron beam sources. Many aspects of his work would fit well into an experimental plan at the intense positron facility that you propose.

IV. Concluding remarks.

I am extremely pleased to learn of your plans to develop a novel intense positron source at SLAC. I am certain that, if it is successful, many groups will find it of use as a new and important tool that will enable a wide range of positron experiments. As described above, our group is taking the next steps in positron trapping. If the SLAC slow positron facility were available, it would be ideal for our purposes. Subject to the availability of funding, I would very much like to participate in experiments there. I have also spoken with Dr. Greaves about your plans, and he too would be interested in collaborating in this effort.

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