HIGH-INTENSITY LOW-ENERGY POSITRON SOURCE AT JEFFERSON LABORATORY

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Abstract

We present a novel concept of a low-energy e^+ source with projected intensity on the order of 10^{10} slow e^+/s. The key components of this concept are a continuous wave e^- beam, a rotating positron-production target, a synchronized raster/anti-raster, a transport channel, and extraction of e^+ into a field-free area through a magnetic plug for moderation in a cryogenic solid. Components were designed in the framework of GEANT4-based (G4beamline) Monte Carlo simulation and TOSCA magnetic field calculation codes. Experimental data to demonstrate the effectiveness of the magnetic plug is presented.

INTRODUCTION

Since the time of the experimental discovery of positronium (Ps), the intensity of low-energy e^+ production has been increased by several orders of magnitude. To date, the highest intensities of slow e^+ are reported in two reactor-based e^+ sources close to 10^9 e^+/s [1, 2]. Achieving an order of magnitude higher than these intensities with high-quality beam brightness not only opens new experimental opportunities in materials science, solid-state and positronium related applications [3, 4], but also significantly reduces the data collection time [5].

In this paper, we present the feasibility study of an advanced intensity low-energy e^+ source based on a Super-Conducting Radio Frequency (SRF) Continuous Wave (CW) e^- linac. Experimental verification of the extraction of e^+ concept is completed and briefly described. Detailed results will be presented in [6].

DESIGN CONSIDERATIONS

Linac-based e^+ sources yield many orders of magnitude higher intensities than those of radioactive emitters. However, the challenging issue of this type of source is the management of the dissipated power in the production target. To address this important issue, we plan to use a rotating production target.

In addition, rastering the incident beam increases the beam spot size, thus reducing the steady state beam spot temperature significantly. Synchronously anti-rastering the emitted e^+ returns the beam center to the nominal spot, thus preserving the brightness of the source. Another important aspect of the proposed design is the transportation of emitted e^+ to an area with sufficiently low radiation and low magnetic field, which creates a suitable environment for high-efficiency cryogenic solid rare-gas moderators.

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LAYOUT OF THE SOURCE

The conceptual layout of the proposed e^+ source is shown in Fig. 1. In the layout, an e^- beam from an SRF linac hits a e^+ production target (converter), and emitted e^+ are transmitted through a channel. The positrons go to the energy moderator after leaving the transport channel.

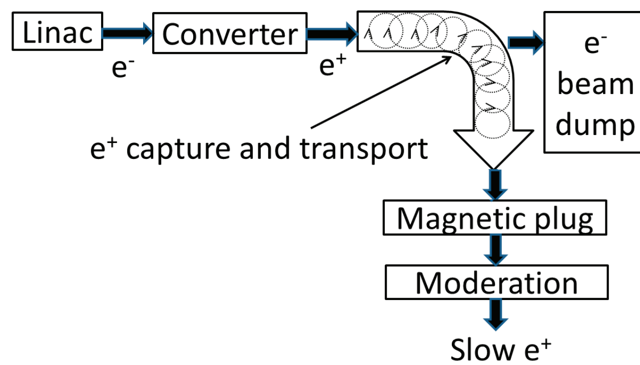

Figure 1: Concept of the low-energy e^+ source.

Super-conducting electron linac

In the current design, we used the e^- beam parameters of the Free Electron Laser (FEL) at Jefferson Lab. The FEL e^- beam is operated in CW mode. The beam has a normalized emittance of $\epsilon_n = 10^{-6}$ m·rad [7]. The energy of the e^- beam can go up to 135 MeV at 1 mA current (in non-recirculation regime).

Production target (Converter)

The interaction of e^- with the production target results in e^+ production inside the target. Let us define the positron-production efficiency (η_+) as the ratio of the number of e^+ to the number of e^- in the incident beam. The η_+ depends on several parameters such as; the target material, its thickness, and the e^- beam energy. We present a comprehensive study where these parameters are varied for Tungsten (W) metal, which is a good choice for positron-production due to its high-Z, durability, and high melting temperature.

Positron energy range The energy spectrum of emitted e^+ is wide ranging up to the incident e^- beam energy. From the whole spectrum, only e^+ that can be moderated to sub-keV (slow e^+) are useful. It is reported that with a specially designed W moderator assembly, e^+ with kinetic energies up to ~ 3 MeV [8] can be moderated with 0.1% efficiency, and in a frozen Neon moderator ~ 600 keV and below can be moderated with 1% efficiency [9].

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Since, our design configuration is primarily based on using high-efficiency cryogenic moderators, we will consider the kinetic energy range below $T_+ < 600$ keV for capture and transport studies. However, as an alternative option, we can use a W moderator, for which we also report e^+ beam parameters after the plug with $T_+ < 5$ MeV. An advantage of using tungsten is that moderator optimization can be enhanced greatly if located in such a low-radiation area.

Target thickness and beam energy study Simulations were performed with three different incident beam energies of 10, 60 and 120 MeV on various thicknesses of W targets to find the optimum production thickness. In Fig. 2, the positron-production efficiency (η_+) as a function of tungsten thickness is shown. In the figure, η_+ represents e^+ in the 2π sr solid angle in the forward direction and with energies up to the spectrum-end. As seen in the

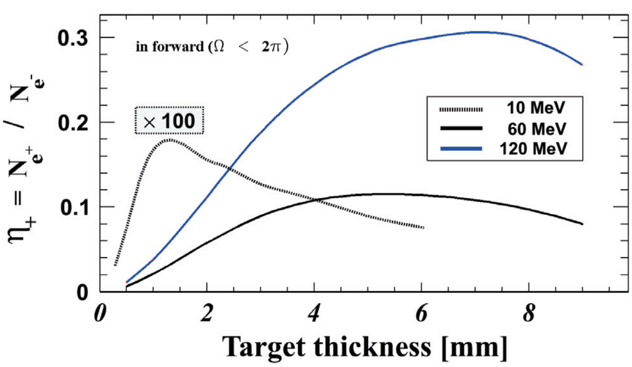

Figure 2: η_+ as a function of the W thickness. The 10-MeV curve is multiplied by 100 for convenience.

figure, with a 120 MeV incident e^- beam, the maximum η_+ is obtained at ~ 6 mm. This maximum η_+ is a factor of three higher than 60 MeV e^- beam and two orders of magnitude higher than 10 MeV e^- beam. As discussed above, we are only interested in capturing the lower part of the e^+ energy spectrum ($T_+ < 600$ keV) and applying this beam on a moderator. For this reason, we consider normalized brightness ($\mathbb{B}_n = \eta_+/\epsilon_x\epsilon_y$) of the beam on the moderator for various converter thicknesses. Here ϵ_x, ϵ_y are transverse emittances of the e^+ beam. In Fig. 3, $\mathbb{B}_n$ at the end of the transport channel is shown. $\mathbb{B}_n$ is calculated at a location after the magnetic plug where a moderator would be positioned. As an example, we took two different W thicknesses for comparison: 2 mm and 6 mm. As it is seen, for $T_+ < 600$ keV, with 6 mm W converter, $\mathbb{B}_n$ is about a factor of three higher than 2 mm W.

Although, 6 mm W thickness ($\sim 2\ X_0$) is favorable due to the nature of the shower mechanism inside the converter, we need to evaluate power deposition in the converter as well. With the assumption of 1 mA incident e^- current, the beam carries 120 kW power. We calculated that $\sim 20\%$ (= 24 kW) of this power is deposited in 6 mm and $\sim 5\%$ (= 6 kW) in 2 mm tungsten. A trade-off between higher intensity and cooling method (water-cooled or rotating target) is the key element when determining converter thickness.

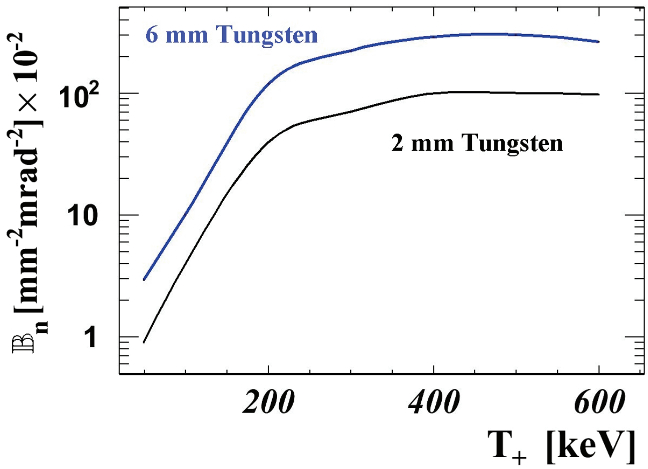

Figure 3: Normalized brightness ($=\eta_+/\epsilon_x\epsilon_y$) of e^+ after the plug with $T_+ < 600$ keV for 2 and 6 mm tungsten thickness.

Description of the transport channel and the plug

The curved transport channel is formed with a solenoidal guide field. The channel transports e^+ away from a high-radiation area, while high energy particles are directed to the beam dump. In Fig. 4, a sketch of the e^+ guide field and magnetic plug concept is shown.

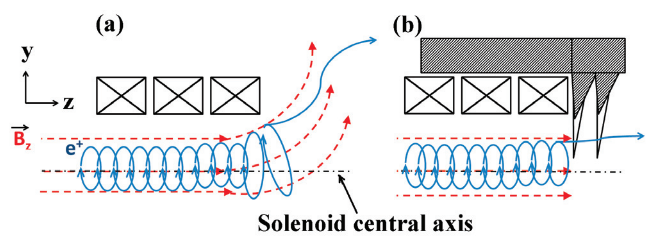

Figure 4: Concept of transport through the solenoid channel (a) without and (b) with the magnetic steel plug. Solid blue lines show e^+ track. Dashed red lines are magnetic field lines. Only the upper half of solenoid is shown.

Due to the curved guiding field frame, the magnetic field in the azimuthal direction has a gradient, which causes a force called grad-B effect. We superimposed a dipole corrector field along the channel to counter this force.

Effectiveness of the magnetic plug

As illustrated in Fig. 4, the extraction efficiency from the solenoid channel is enhanced with rapid extinction of the guide field.

Otherwise, the lowest energy, and most desirable e^+, will follow the diverging field lines into material surfaces and be lost. Thus, we designed a magnetic iron plug to be inserted at the end of the solenoid for transition to a field-free area, which is similar to a magnetic spider [10]. We

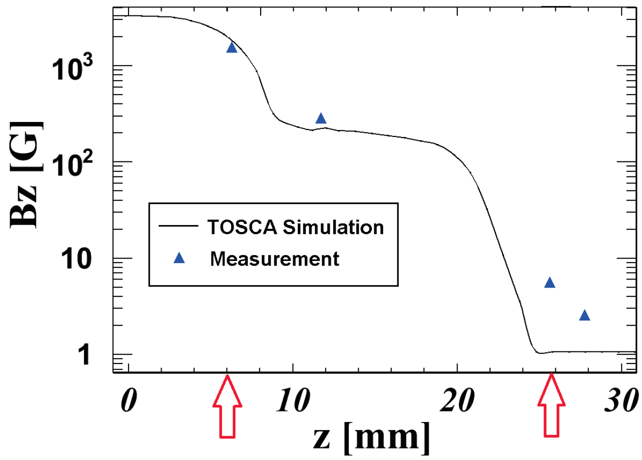

Figure 5: Simulation and measurement comparison of the prototype magnetic plug. Arrows indicate span of the plug.

Incident e^- beam	[MeV]	120
η_+ **at W target**		
$T_+ < 0.6$ MeV	[e+/e-]	$6.0{\times}10^{-4}$
$T_+ < 5.0$ MeV	[e+/e-]	$3.1{\times}10^{-3}$
η_+ **after plug**		
$T_+ < 0.6$ MeV	[e+/e-]	$2.0{\times}10^{-4}$
$T_+ < 5.0$ MeV	[e+/e-]	$1.7{\times}10^{-3}$

Table 1: Comparison of η_+ right after the converter and at the exit of the magnetic plug for 120 MeV incident e^- beam on a 2 mm converter.

designed and constructed a simpler prototype to compare magnetic field termination and e^+ transmission characteristics against our calculations. A detailed description of the plug will be presented in [6]. In Fig. 5, the TOSCA simulation and experimental results are compared for the prototype. The simulation and data are in good agreement that the plug reduced the field from $B_z \sim 2$ kG to an order of a few Gauss with modest loss of the e^+ intensity.

Simulation results of e^+ transport

In our design, positron-production, solenoid channel, and magnetic plug simulations are completed with various codes (GEANT4 based G4beamline and TOSCA). By using the optimized plug, about 50% of e^+ that are transported to the entrance of the plug are transmitted through the plug within 5 mm r.m.s transverse beam spot size. In Table 1, simulation results of production and transport efficiencies for 120 MeV e^- beam incident on a 2 mm converter are shown. The η_+ after the plug do not have any cuts except due to the transport channel acceptance.

Neither solid Neon nor W moderator assemblies are included in the simulations. However, we present the efficiencies for two energy ranges of e^+, which are able to penetrate the magnetic plug.

DISCUSSION AND CONCLUSION

We have presented the feasibility study of a e^+ source that can be used in production of a moderated slow e^+ beam. Optimization of both incident e^- beam and emitted e^+ beam parameters are completed through analytical and numerical studies.

The curved solenoid channel with a magnetic iron plug at the end of this channel allows us to successfully transport a majority of the created positrons from a high radiation area to a low radiation and low magnetic field area. This allows us to use high-efficiency delicate noble-gas moderators.

The η_+ values given in Table 1 can be translated into slow e^+/s. For a 1 mA incident e^- beam $\sim 1 \times 10^{12}$ e^+ ($T_+ < 0.6$ MeV) can be transported to the moderator. By using the projected moderator efficiency of 1% for solid Neon, it is possible to obtain 10^{10} slow e^+/s with 2 mm thick ($\sim 3 \times 10^{10}$ with 6 mm) converter.

In the alternative case, where a W moderator is used instead of a solid rare-gas, $\sim 1 \times 10^{13}$ e^+ ($T_+ < 5$ MeV) can be transported to the moderator. With 0.1% moderation efficiency, it is possible to obtain 10^{10} slow e^+/s with this option as well. The anticipated performance of this design significantly exceeds the best reported results from reactor or other available e^+ sources.

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