PROCEEDINGS OF SCIENCE

Liquid metal-based polarized positron generation benchmark using the Geant4 toolkit

PoS(PSTP2024)073

V. M. Lizarraga-Rubio,[a,*] **A. Sy,**[b] **A. Ushakov,**[b] **J. Grames,**[b]
C. A. Valerio-Lizarraga[c] **and V. Kostroun**[d]

[a] *Universidad de Guanajuato, Leon, Guanajuato, Mexico*
[b] *Thomas Jefferson National Accelerator Facility, Newport News, VA, USA*
[c] *Universidad Autonoma de Sinaloa, Culiacan, Sinaloa, Mexico*
[d] *Xelera Research LLC, Ithaca, NY, USA*

E-mail: `vm.lizarragarubio@ugto.mx`

In this work, we report simulation results for the positron yield and polarization of polarized electron beams incident on GaInSn and PbBi liquid metal targets. One of the proposed upgrades to 12 GeV CEBAF is the use of a continuous wave polarized positron beam for physics experiments. High-Z liquid metal jets are excellent candidates for positron production targets because they can withstand high power beams. Polarized positron beams can be generated from a primary electron beam incident on a thick high-Z target through circular polarized bremsstrahlung conversion to linearly polarized pair production. This polarization transfer from the primary electron beam has been previously demonstrated at Jefferson Lab in the PEPPo experiment with a tungsten target at low energies. Here we report Geant4 simulations for 10 and 120 MeV electron beams incident on GaInSn and PbBi liquid metal targets. These simulations are compared to simulations with a solid tungsten target, as well as with unpolarized simulations using MCNP6.

20th International Workshop on Polarized Source, Targets, and Polarimetry
22-27 September 2024
Jefferson Lab, Newport News, Virginia, USA

---

[*] Speaker

ISSN 1824-8039. Published by SISSA Medialab.
https://pos.sissa.it/

1. Introduction

One of the proposed upgrades of 12 GeV CEBAF at Jefferson Lab is the addition of a continuous wave polarized positron beam for nuclear physics experiments [1]. The proposed positron source is bremsstrahlung-based, where a drive electron beam generates bremsstrahlung radiation from the interaction inside the target material. This radiation is converted into electron-positron pairs, leaving the positrons to be collected into a particle beam. The longitudinal polarization of the drive electron beam is partially transferred to the gamma rays as circular polarization, which is then partially transferred to longitudinal polarization to the secondary positrons. One of the most critical challenges for this kind of positron source is managing the deposited power in the target. One proposed solution is the use of a free surface high-Z liquid metal jet since it can act as both the positron source and the coolant. The aim of this work is to show preliminary simulations of the expected polarized positron generation in a liquid metal target (in overall yield and polarization), as well as a study of the energy deposition dependency on the drive electron beam energy.

2. Liquid metal target prototype

The first phase of the liquid metal jet source consists of a device that has a closed loop of recirculating liquid metal. The main components are the liquid metal reservoir, the pump and the heat exchanger. The liquid metal jet is shaped by a nozzle designed to maintain a uniform jet thickness of 3 mm throughout the beam facing region. In this first prototype, the working liquid metal is a GaInSn eutectic, a mixture of Gallium (67 wt%), Indium (20.5 wt%) and Tin (12.5 wt%). This material has a relatively low effective Z, meaning the expected positron yield is low. However, it was selected as it has material properties similar to the PbBi eutectic, Pb 44.5 wt%, Bi 55.5 wt%, but unlike PbBi, which has to be heated to an operating temperature of 150°C, GaInSn is a liquid at room temperature. This helps bypass the need for heating the whole chamber, simplifying this first design. Please see [2] for more details about the prototype.

3. Polarized positron generation simulations

The positron generation simulations were performed using two different codes. The main one is Geant4 [3], a simulation toolkit that has the capabilities of modeling the beam interaction with matter and external electromagnetic fields. The Geant4 toolkit also allows for the tracking of polarization of the simulated particles, enabling the study of the polarization transfer from the drive electron beam to secondary particles.

The simulation is limited to the beam-target interaction, excluding any other components. The target is modeled as a stationary slab made out of the different relevant materials with a uniform distribution. The simulated drive electron beam is mono-energetic, with no initial transverse momentum, and a Gaussian transverse spatial distribution. Figure 1 shows an example of a Geant4 simulation of a drive electron beam incident on a target generating a shower of secondary particles. The most relevant properties of the generated polarized positrons are the positron yield, ε, the mean longitudinal polarization, $\langle P_z \rangle$, and a figure-of-merit defined by FOM $= \varepsilon \langle P_z \rangle^2$. The figure-of-merit is an important parameter for polarization experiments, as optimizing it decreases measurement error or reduces experiment time.

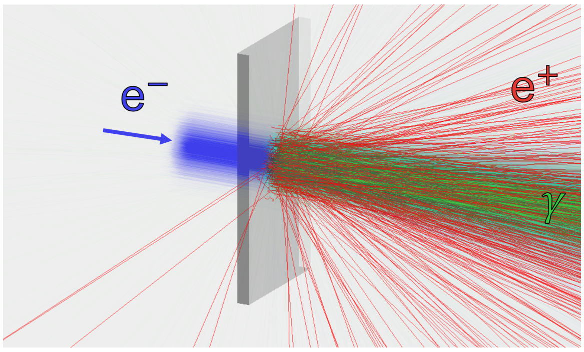

Figure 1: Visualization of an example of a Geant4 simulation. The electron beam hits a target and produces a shower of gamma rays and electron-positron pairs.

Polarized positron generation comparison between Geant4 and MCNP6

The first result is a comparison of simulations of the positron generation with Geant4 and MCNP6 [4]. The electron beam kinetic energy is 10 MeV. The root-mean-squared (RMS) beam spot size is 1 mm in both transverse coordinates. The target material is GaInSn and the thickness is varied to monitor its effect on the overall positron yield. The target thickness varies from 0.125 mm to 8 mm. The positron yield is calculated from the number of positron that leave the target from the downstream side. No angular cuts are applied. The minimum total number of primary electrons is 10 billions and is adjusted to increase statistics of plotted quantities. Fig. 2 shows a comparison of the positron yield as a function of the target thickness, showing very good agreement between the two codes. The optimum target thickness is found to be between 4 and 5 millimeters. The positron yield per primary electron at different energy bins is shown for different GaInSn jet thicknesses in Fig. 3 for both Geant4 and MCNP6.

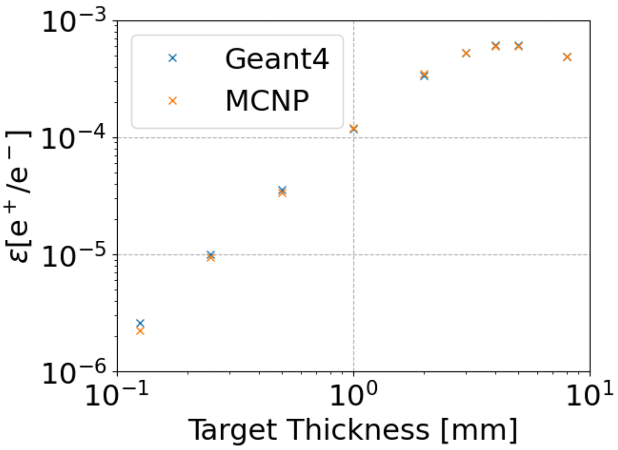

Figure 2: Comparison of the overall positron yield calculated with Geant4 and MCNP6 for a 10 MeV electron beam incident on a liquid GaInSn jet of different thicknesses.

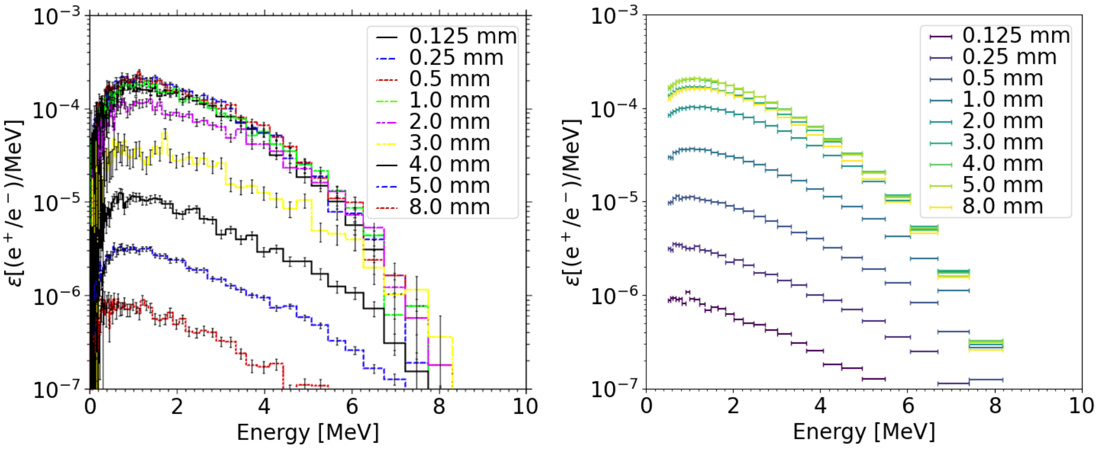

Figure 3: Positron yield [e^+/e^-/MeV] for a 10 MeV electron beam incident on a liquid GaInSn jet of variable thickness for MCNP6 (left) and Geant4 (right).

Comparison of polarized positron generation in solid and liquid targets

The second result is a comparison of the polarization relevant quantities of the generated positrons using a liquid PbBi target and a solid tungsten one. These simulations were performed with Geant4. The electron beam kinetic energy is 120 MeV. The RMS beam spot size is 1 mm in both transverse coordinates. The liquid metal jet and solid target thicknesses are varied to find the optimum for maximum positron yield and FOM. A comparison of the resulting polarization quantities of the generated positrons at different energy bins is shown in Fig. 4 for both target materials and different jet thicknesses. The bin size is 10% of the central energy of the bin. The overall maximum positron yield is the same for both target materials, however the optimum thickness is 7 mm for tungsten, and 11 mm for liquid PbBi. These values are close in units of their corresponding radiation length, X_0 (approximately $2X_0$). The overall positron polarization increases with target thickness for both materials. The mean longitudinal polarization at maximum yield and maximum FOM as a function of target thickness is shown in 5. At the energy bin with maximum yield, the positron polarization increases with jet thickness and has a maximum of 30 %. At the energy bin with maximum FOM, the positron polarization decreases with target thickness and has a maximum around 80%. While the observed trends are consistent with previous results [5], the values obtained should be reevaluated when considering the effect of a downstream collection system.

Power deposition study of GaInSn target

The final result is a study of the energy deposition in a liquid GaInSn jet as a function of the drive electron beam energy. These simulations were performed using FLUKA [6]. The selected beam kinetic energy values were 2.5 MeV, 5 MeV, 7.5 MeV and 10 MeV. The RMS beam spot size is 1 mm in both transverse coordinates. The jet thickness is fixed at 3 mm for these simulations. The deposited energy density at $r = 0$ (beam axis) is shown in Fig. 6 for different drive beam energies. Lower energy beams have a larger peak deposited energy density than higher energy beams. This is derived from the fact that lower energy beams deposit most of its power closer to the upstream face, while higher energy beams have a flatter deposited energy density profile.

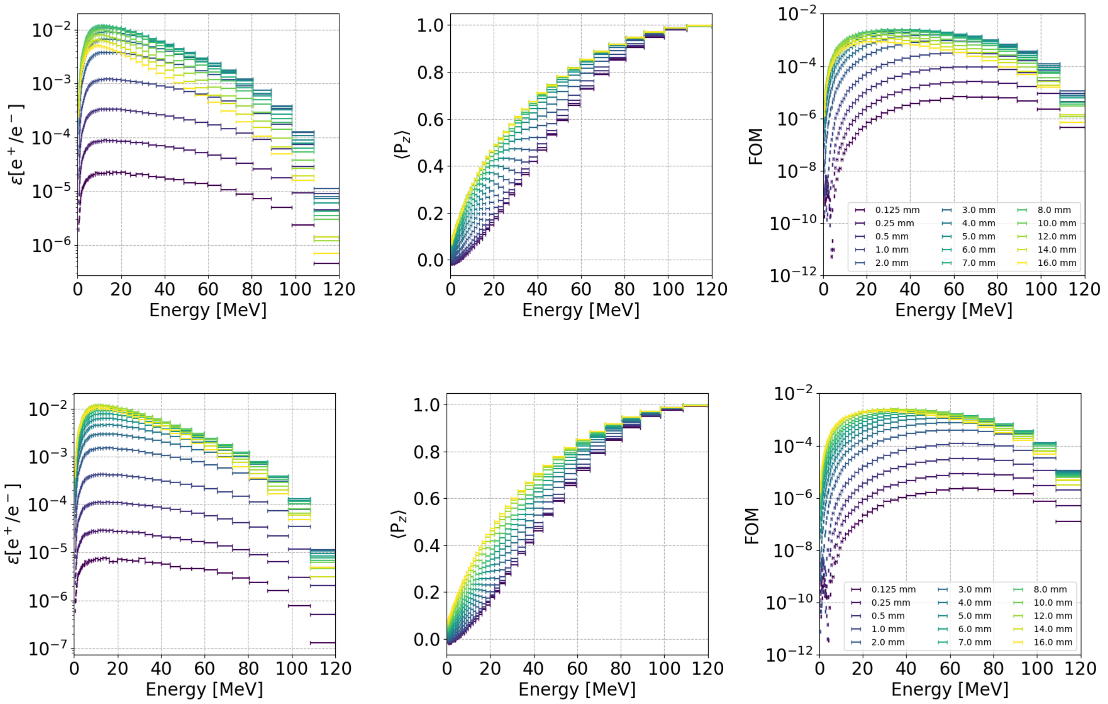

Figure 4: Polarization relevant quantities as a function of positron energy from Geant4 simulations of a 120 MeV electron beam incident on a solid tungsten target (top) and a liquid PbBi jet (bottom). Different target thicknesses are represented by different colors. Energy bin size is 10 % of the central energy of each bin. The minimum total number of primary electrons is 10 million.

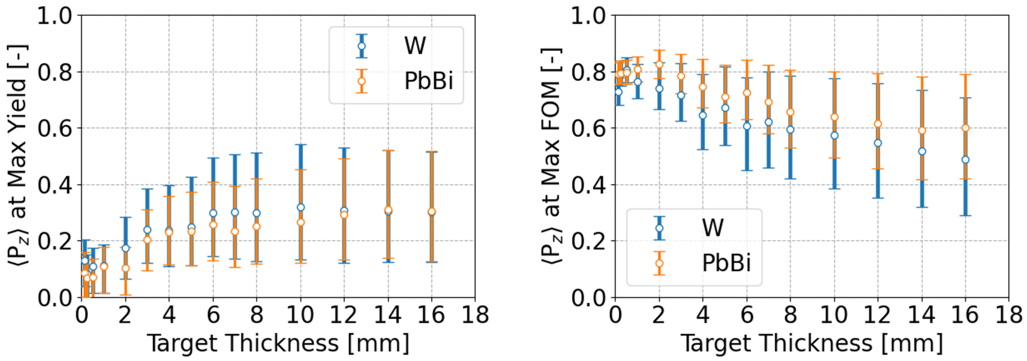

Figure 5: Comparison of the mean positron polarization at the positron energy bin with maximum positron yield (left) or maximum FOM (right) from Geant4 simulations of a 120 MeV electron beam incident on a solid W target and a liquid PbBi jet with variable thicknesses. The marker represents the mean value. The error bars represent the 16th and 84th percentiles. The minimum total number of primary electrons is 10 million.

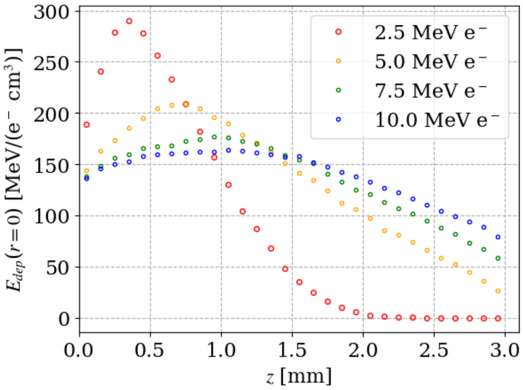

Figure 6: Deposited energy density as a function of target depth for different drive electron beam energy. The minimum total number of primary electrons is 5 million, adjusted to reduce noise in the deposited power profile.

4. Future work

The design and installation of a GaInSn test beam line at the Low Energy Recirculator Facility (LERF) at Jefferson Lab are currently in progress. Additional studies including energy deposition simulations in the liquid metal are being done in parallel with the results presented in this work. Finally, a study of the feasibility of a liquid PbBi target test at 120 MeV for higher polarized positron yield is also planned.

5. Conclusions

A liquid metal target is a good candidate for a polarized positron source. The optimum jet thickness for positron production of different liquid metals at different drive electron beam energies was found. For GaInSn at 10 MeV the optimum thickness lies between 4 and 5 millimeters. At 120 MeV beam energy, the optimal jet thickness of a PbBi jet is 11 mm, compared to 7 mm for a tungsten target. The maximum positron polarization for maximum yield increased with jet thickness and has a maximum of 30%. For maximum FOM, the maximum positron polarization decreases with jet thickness and has a maximum of 80% for thinner targets.

Acknowledgements

This project is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177 and SBIR Program under grant number DE-SC0023574. Partial financial support was received from National Council of Humanities, Sciences and Technologies (CONAHCYT) under fellowship No. 923720.

References

[1] A. Accardi et al., *An experimental program with high duty-cycle polarized and unpolarized positron beams at Jefferson Lab*, Eur. Phys. J. A **57** (2021) 261 [`2007.15081`].

[2] N. Taylor et al., *A high-power positron converter based on a recirculated liquid metal in-vacuum target*, in *Proc. IPAC'24*, pp. 1210–1213, JACoW Publishing, Geneva, Switzerland, 2024.

[3] S. Agostinelli et al., *Geant4 — a simulation toolkit*, *Nucl. Instrum. Methods Phys. Res. A* **506** (2003) 250.

[4] T. Goorley et al., *Initial MCNP6 release overview*, *Nucl. Technol.* **180** (2012) 298.

[5] S. Habet et al., *Characterization and optimization of polarized and unpolarized positron production*, Tech. Rep. PEPPo TN-23-01, JLAB-ACC-23-3794, Jefferson Lab (2023), [2401.04484].

[6] G. Battistoni et al., *Overview of the FLUKA code*, *Ann. Nucl. Energy* **82** (2015) 10.