Using a Liquid Xenon Positron Target

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Colliding high energy electrons with a high-Z material – known as a positron target – is a common method for producing positrons for particle accelerator applications. The main consequence of using a solid positron target involves material degradation due to energy deposition from the beam, in which preventative measures require various techniques to dissipate thermal gains in the material. Rather than investigating the techniques to obviate the solid target problems, we explore the use a liquid Xenon positron target as an alternative to using solid targets. From simulations in GEANT4, we find that a liquid Xenon target has positron yields on the order of currently implemented solid targets while also maintaining comparable positron emittances and energies. With thoughtful design of a liquid Xenon chamber, we argue that one can more easily account for the energy deposits from the beam as compared to currently used solid targets.

I. INTRODUCTION

A common scheme for producing positrons is by colliding high energy electrons into a high-Z target. The collision between an electron beam and a target generates an electromagnetic particle shower in which positrons are produced. Because the collision is such high energy, a great deal of energy is deposited in the target in the form of thermal energy. As a result, solid targets tend to degrade over time []. Starting from thicknesses less than one radiation length, positron yield increases as a function of target width until achieving a maximum yield thickness []. Therefore, a thicker target implies a greater positron yield to some extent, but that also results in a greater energy deposited into the target leading to a quicker degradation of the target.

There are various methods for increasing the life span of solid targets, such as using a cooling system [] and rotating the target so that the beam doesn't hit the same spot of the target every beam pulse [].

Previous experiments have been carried out to explore alternatives to using solid targets, such as using liquid Mercury (Hg), but the apparent hazards that Hg presents are too dangerous to implement in any efficient manner. Other approaches include using liquid Lithium to generate secondary particles [], as well as using gaseous deuterium for muon related studies []. The use of liquid Lithium fails in the respect that efficient positron targets need to have a high number of protons per atom [].

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For current and future Linear Collider applications, around 10^{14} e^+ per second need to be produced [].

In this paper, we explore the possibility of using a liquid Xenon (Xe) target to produce positrons.

II. SIMULATION RESULTS

A. Comparing Liquid Xenon and Tantalum Targets

Various experiments have been performed with the use of a Tantalum positron target []. We use GEANT4 to simulate positron production in both a Tantalum target and a liquid Xenon target. Since Tantalum targets are well established in the realm of positron production, it serves as a proper benchmark for liquid Xenon.

See Table I for parameters used in the simulation.

Material	Symbol	Z	Density [g·cm^{-3}]	Radiation Length [cm]
Tantalum	Ta	73	16.654	0.4094
Liquid Xe	lXe	54	2.953	2.872

TABLE I: Parameters used in GEANT4 simulation when comparing targets.

1. Calculating Positron Emittance

To calculate the RMS emittance of the positrons generated in pair production, we utilize the following sets

of equations []

$$\left\langle x^2 \right\rangle = \frac{\sum x^2}{n} - \left(\frac{\sum x}{n}\right)^2, \tag{1a}$$

$$\left\langle p_x^2 \right\rangle = \frac{\sum p_x^2}{n} - \left(\frac{\sum p_x}{n}\right)^2, \tag{1b}$$

$$\left\langle x p_x \right\rangle = \frac{\sum x p_x}{n} - \frac{\sum x \sum p_x}{n^2}, \tag{1c}$$

which gives us

$$\varepsilon_{n,rms} = \frac{1}{m_0 c}\sqrt{\left\langle x^2 \right\rangle \left\langle p_x^2 \right\rangle - \left\langle x p_x \right\rangle}. \tag{2}$$

Using these equations, we generate a plot of the x- and y-emittance of the positrons against target width for both Tantalum and liquid Xenon targets. As seen in Figure 1, both the x- and y-emittance of the positrons are lower in the Tantalum target than in the liquid Xenon target. According to [], the emittance values associated with liquid Xenon are still comparable for use in linear colliders.
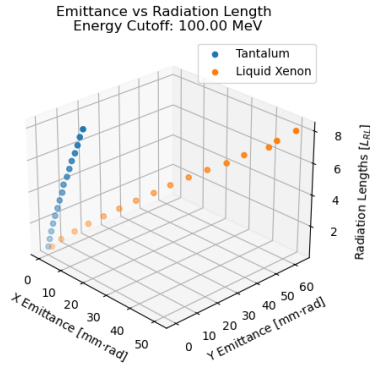
FIG. 1: Normalized RMS positron emittance in a Tantalum and liquid Xenon target for differing target widths. The positron energy cutoff was set to 100 MeV.

In simulation, we compare the energy deposited in the target for both materials for each incident electron. Although compared to [] these proportions are quite high, as we indicate in Section III A, the flow of liquid Xenon can take into account the energy deposit without much concern.
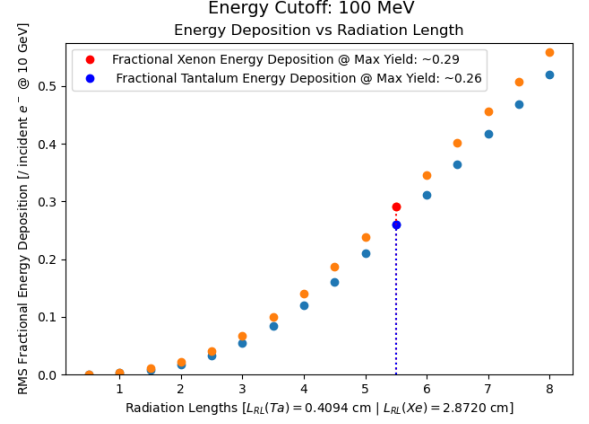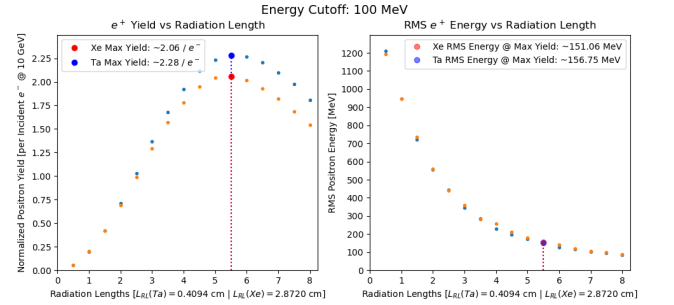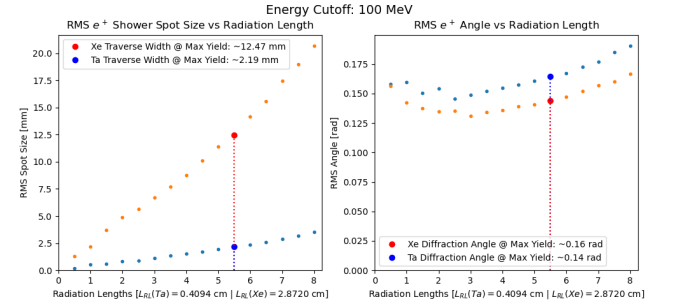

FIG. 2: Energy deposition in Ta and lXe targets per incident electron at 10 GeV.
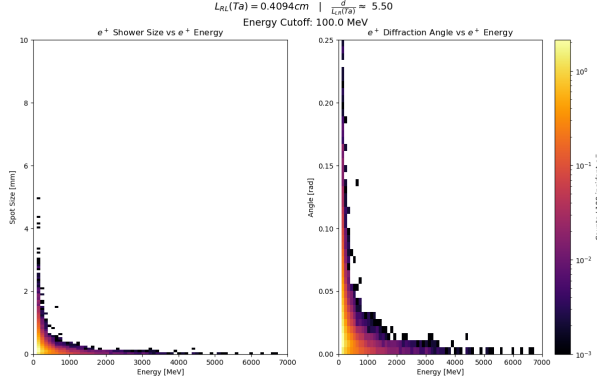

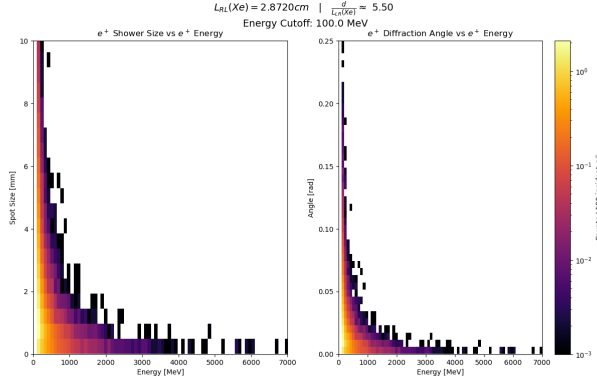
(a) Positron yield and energy at target exit.
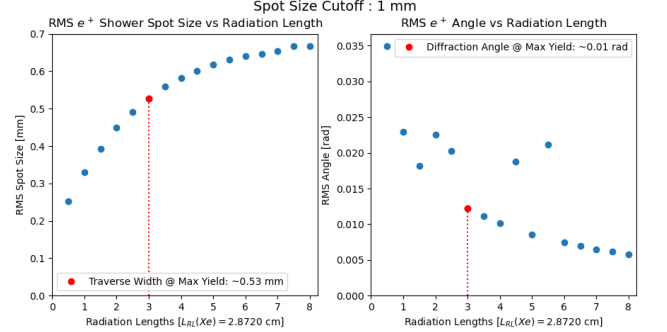
(b) Positron shower spot size and diffraction angle at the exit of the target.

FIG. 3: Positron yield and RMS energy, shower spot size, and angular divergence of positrons upon exiting the target per incident e^- at 10 GeV.

From Figure 3a, the max positron yield for both Ta and lXe occurs at around 5.5 radiation lengths. Despite having different radiation lengths, the energy of the positrons exiting the target at a given width are relatively equal for both target materials.
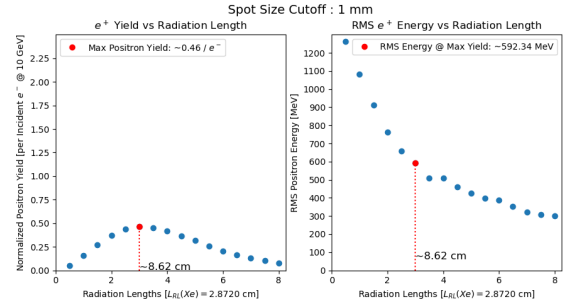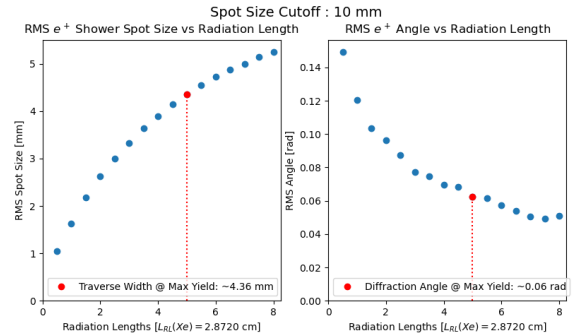
It is reassuring to see that even after removing the positrons from the dataset with large transverse distances from the beam path, there are still a comparable number of positrons that we predict will be able to make it to the next stage of the accelerator [].

III. CRYO-COOLED LIQUID XENON CHAMBER

Figure 7, a basic schematic of how the liquid Xenon chamber will interact with the beam.

FIG. 7: Schematic of liquid Xenon setup.

A. Calculating the Liquid Xenon Flow Rate

To calculate the flow rate of the liquid Xenon, we first calculate preliminary values using the information given in the table below.

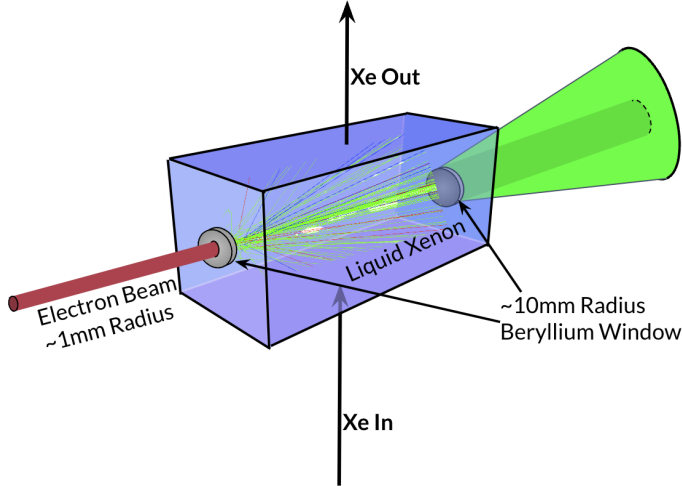| Liquid Xenon	Symbol	Value	Units
Molar Mass	M	131.293	u
Density	ρ	2.953	$g \cdot cm^{-3}$
Heat of Vaporization	ΔH	12.636	$kJ \cdot mol^{-1}$
Heat of Vap./Volume	ΔH_{vol}	284.205	$J \cdot cm^{-3}$
Radiation Length	L_{RL}	2.872	cm
Width	$\frac{d}{L_{RL}}$	5.5	L_{RL}

TABLE II: Important parameters associated with liquid Xenon target chamber.

We first convert the heat of vaporization to units of Joules per unit volume ($J \cdot cm^{-3}$), which is given by Eq. (3a). We then calculate the number of electrons per beam bunch (SLAC), by comparing the total charge of the beam bunch to the charge of an electron ($e \approx 1.602 \times 10^{-10}$ nC), as follows from Eq. (3b). From this, we calculate the total energy deposited in the liquid Xenon

target, as seen in Eq. (3c).

$$\Delta H_{vol} = \frac{\Delta H \cdot \rho}{M}, \tag{3a}$$

$$n = \frac{q}{e}, \tag{3b}$$

$$\epsilon = n \cdot E_{dep}. \tag{3c}$$

Now we have everything we need in order to calculate the flow rate of liquid Xenon required to replace the vaporized Xenon due to the energy deposited by the beam,

$$Q = \frac{\epsilon \cdot f}{\Delta H_{vol}}. \tag{4}$$

In case one wants to calculate the flow rate required to move the entire volume encompassing the main part of the EM shower, one can approximate the volume with a rectangular prism with target width and other side lengths equal to the diameter of the Beryllium windows (see next section). At max positron yield, this gives $V = (2 \text{ cm})^2 \cdot 5.5 L_{RL} \approx 63.18 \text{ cm}^3$. As a result, the required flow rate to move volume V in the amount of time between beam pulses is shown in Table III as Q_{vol}.

B. Using Beryllium Windows to the Target Chamber

We explore using Beryllium windows for the beam to enter the target chamber. Below is some useful information about Beryllium.

Utilizing Bernoulli's Equation for conservative force fields [], we can calculate the total pressure on a Beryllium window, which is of the form

$$P = \frac{1}{2}\rho v^2 + \rho gh + p, \tag{5}$$

where v is the fluid flow rate, g is acceleration due to gravity, h is the height of the Xenon chamber relative to the height of the window, and p is the additional pressure from, say, the atmosphere. However, as seen in Table III, the flow rate for the liquid Xenon is quite small. Additionally, the liquid Xenon chamber is in vacuum, and we are comparing differences in total pressures, so we can ignore p as well. Therefore, we can ignore the second order term and the point-pressure term to further simplify our approximation to

$$P = \rho gh. \tag{6}$$

From Eq. (6), we can calculate the force on a Beryllium window with contact area A by multiplying the area by the pressure: $F = P \cdot A$.

In order to determine the required thickness of the Beryllium window, we utilize the following []. First we calculate a constant related to the safety factor of our thickness, which takes into account the method with

Beam Parameters	Symbol	FACET-II	ILC	Units
Energy	E	10.0	6.0	GeV
Repetition Rate	f	10	300	Hz
Charge	q	2	3.204	nC
Number of e^-	n	1.248	2.0	10^{10}
Resultant Quantities				
Energy Deposition/e^-	E_{dep}	.66581		GeV
Energy Deposit/Pulse	ϵ	1.332	735.9	J
Energy Deposit Density	ϵ_ρ	1.63×10^{-3}	3.10	J·g^{-1}
Power Deposit	P_{dep}	3.86	7.359×10^8	W
Flow Rate due to Vaporization	Q	4.685×10^{-2}	776.8	cm$^3 \cdot$ s^{-1}
Main Shower Path Flow Rate	Q_{vol}	0.6318	18.96	L·s^{-1}

TABLE III: Linear collider electron beam parameters and associated target quantities [].

Beryllium	Symbol	Value	Units
Atomic Number	Z	4	
Density	ρ	1.844	g·cm^{-3}
Rupture Modulus	F_a	400	MPa
Quantities			
Height [a]	h	1.0	m
Radius	r	10.00	mm
Contact Area	A	100π	mm^2
Pressure	P	28.968	kPa
Force	F	9.100	N
Safety Factor	S_F	4	
Empirical Constant	K	0.75	
Thickness	T	147.395	μm

[a] Difference in height between the Beryllium window and the top of the liquid Xenon chamber.

TABLE IV: Useful quantities and properties of solid Beryllium. The quantities are specific to a 10mm radius Beryllium disk.
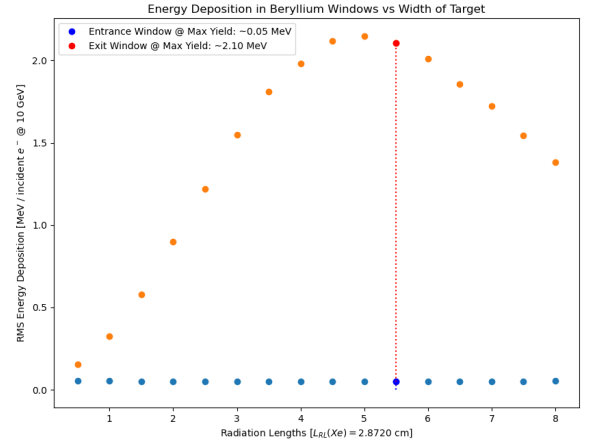

FIG. 8: Energy deposition on incident and exit Beryllium windows.

which the Beryllium window is inserted into the target chamber. An empirical constant $K = 0.75$ is chosen if the window is clamped into the target chamber, and $K = 1.125$ if the window is unclamped in the target chamber. For a given safety factor (S_F), we have a thickness of

$$T = r \cdot \sqrt{\frac{S_F \cdot K \cdot P}{F_a}}. \tag{7}$$

IV. CONCLUSION

A. Design of Liquid Xenon Chamber

Here we explore how one could design a chamber for the liquid Xenon target.

Source code and sample data for GEANT4 simulations can be found at https://github.com/MaxVarverakis/LiquidXenonSims.git.

ACKNOWLEDGMENTS

Appendix A: Appendixes

To start the appendixes, use the `\appendix` command. This signals that all following section commands refer to appendixes instead of regular sections. Therefore, the `\appendix` command should be used only once—to setup the section commands to act as appendixes. Thereafter normal section commands are used. The heading for a section can be left empty. For example,

```
\appendix
\section{}
```

will produce an appendix heading that says "APPENDIX A" and

```
\appendix
\section{Background}
```

will produce an appendix heading that says "APPENDIX A: BACKGROUND" (note that the colon is set automatically).

If there is only one appendix, then the letter "A" should not appear. This is suppressed by using the star version of the appendix command (`\appendix*` in the place of `\appendix`).

Appendix B: A little more on appendixes

Observe that this appendix was started by using

```
\section{A little more on appendixes}
```

Note the equation number in an appendix:

$$E = mc^2. \tag{B1}$$

1. A subsection in an appendix

You can use a subsection or subsubsection in an appendix. Note the numbering: we are now in Appendix B 1.

Note the equation numbers in this appendix, produced with the subequations environment:

$$E = mc, \tag{B2a}$$
$$E = mc^2, \tag{B2b}$$
$$E \gtrsim mc^3. \tag{B2c}$$

They turn out to be Eqs. (B2a), (B2b), and (B2c).