Using a Liquid Xenon Positron Target

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ABSTRACT

Usage: Secondary publications and information retrieval purposes.

Structure: You may use the `description` environment to structure your abstract; use the optional argument of the `\item` command to give the category of each item.

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 solid 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 []. Since positron yield increases as a function of radiation length [], a thicker the target implies a greater positron yield, but that also implies a greater energy will 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 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...

For typical Linear Collider applications, around *** 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 Xe and Ta Targets

Comparison study between Tantalum (Ta) and liquid Xe because we have a reference study on Ta []. We used GEANT4 to simulate the collision between 10 GeV e^- and a target. We compare the results of using a Ta target and a liquid Xe target.

See Table I for parameters used in the simulation.

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

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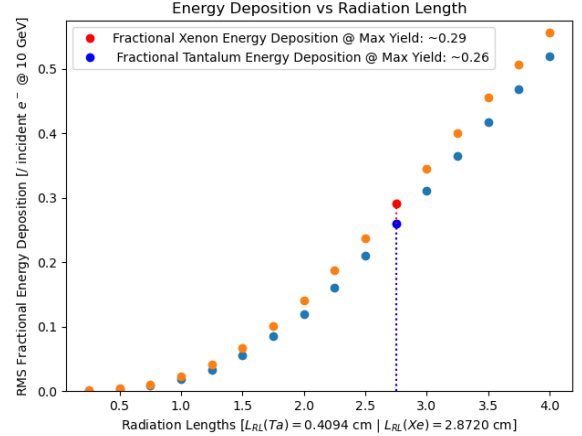

FIG. 1: Energy deposition in Ta and liquid Xe targets per incident electron at 10 GeV.

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 2, 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.
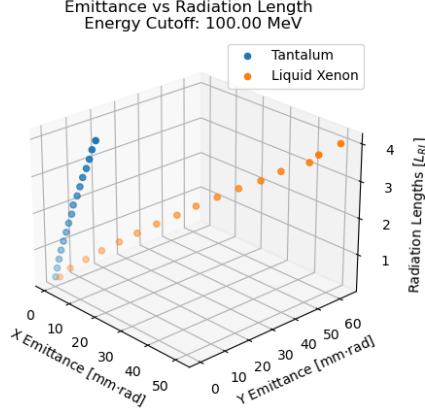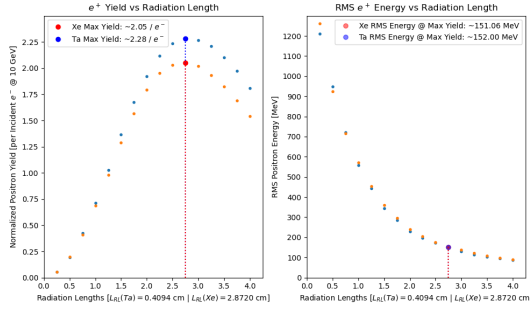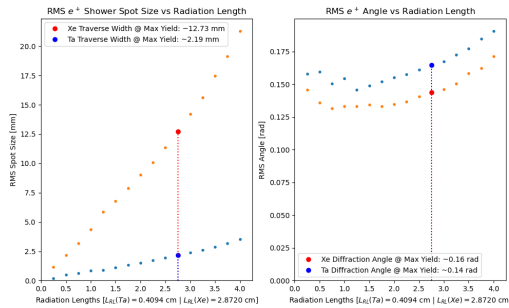

FIG. 2: Normalized RMS positron emittance in a Tantalum and liquid Xenon target for differing target widths. The positron energy cutoff was set to 100 MeV.
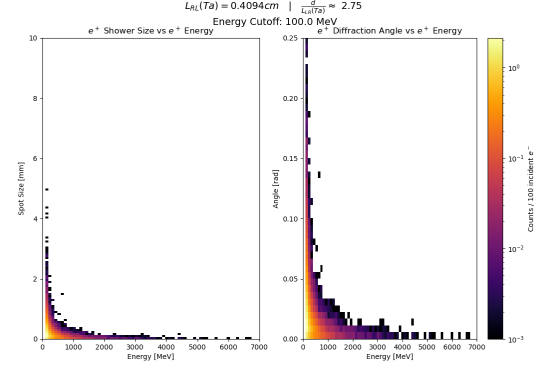

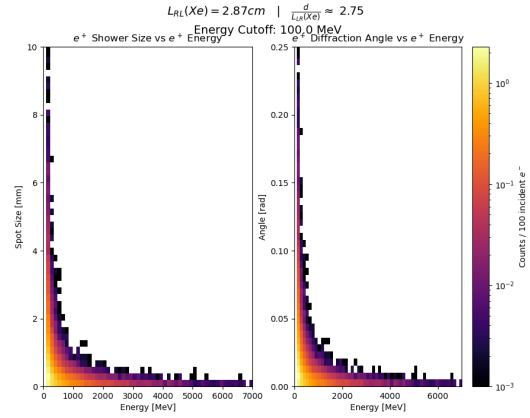(a) Positron yield per incident electron at 10 GeV.

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

FIG. 3

As seen in Figure 3a, the max positron yield for both Ta and liquid Xe occurs at around 2.75 radiation lengths.

(a) Tantalum target.
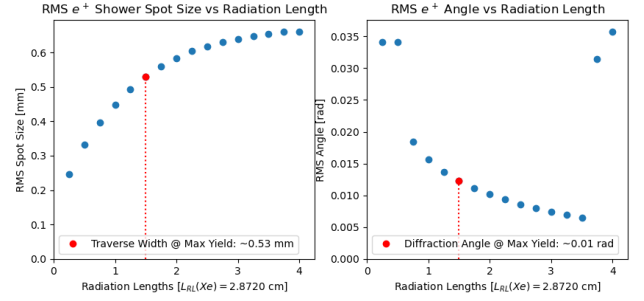

(b) Liquid Xenon target.

FIG. 4: Traverse width and angular diffraction of positrons as a function of their energy upon production. Data is shown for widths of 2.75 radiation lengths (max e^+ yield).

Notice that in Figure 4, the angular divergence of positrons is roughly the same for both targets, yet the traverse widths are more broadly distributed for the liquid Xenon target. This can be explained by the fact that the radiation length of liquid Xenon is roughly seven times that of Tantalum.

B. Setting a Cutoff Traverse Width

Although the max yield for liquid Xenon is on par with that of the Tantalum target according to Figures 3b and 4, the physical spread of positrons produced from the liquid Xenon target is much larger than that of the Tantalum target. As a result, only a fraction of the positrons that exit the target will have the right characteristics to make it down the rest of the accelerator. In order to accurately assess the plausibility of using

a liquid Xenon positron target, we set cutoffs for the traverse width of positrons created during the collision.
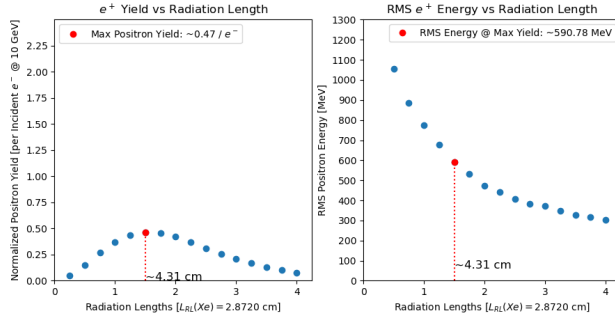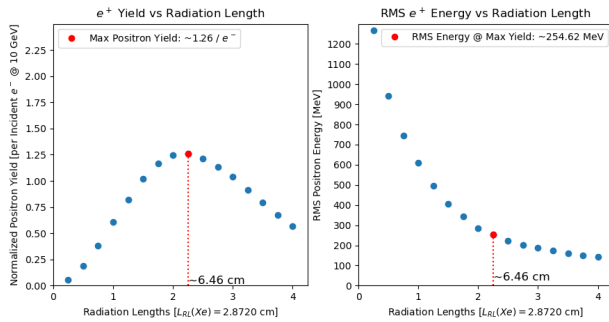

(a) 1 mm cutoff
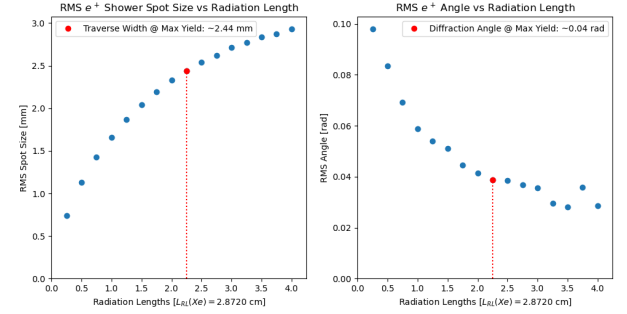
(b) 5 mm cutoff

FIG. 6: Positron spot size and angular diffraction using a liquid Xenon target with a 1 mm and 5 mm traverse width cutoff.

(a) 1 mm cutoff

(b) 5 mm cutoff

FIG. 5: Positron yield and energy using a liquid Xenon target with a 1 mm and 5 mm traverse width cutoff.

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.
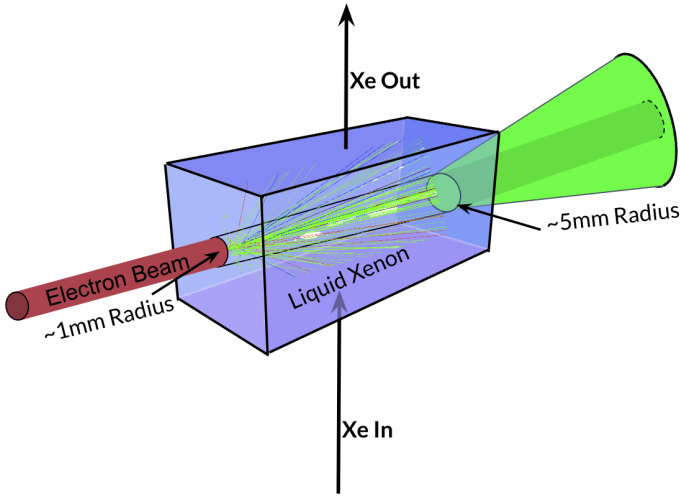
FIG. 7: Schematic of liquid Xenon setup.

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.

Quantity	Symbol	Value	Units
Molar Mass	M	131.293	u
Heat of Vaporization	ΔH	12.636	kJ·mol^{-1}
Radiation Length	L_{RL}	2.872	cm
Target Width	$\frac{d}{L_{RL}}$	2.25	L_{RL}
Energy Deposition per e$^-$	E_{dep}	.66581	GeV
Beam Rep Rate	f	10.0	Hz
Beam Charge	q	2.0	nC
Target Density	ρ	2.953	g · cm^{-3}
Calculated Quantities			
Number of e$^-$	n	1.248×10^{10}	
Energy Deposit per Bunch	ε	1.33162	J
Heat of Vap. per Volume	ΔH$_{vol}$	284.205	J·cm^{-3}
Flow Rate	Q	4.685×10^{-2}	cm^3 · s^{-1}

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·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).

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

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

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

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,

$$Q = \frac{\varepsilon \cdot f}{\Delta \text{H}_{\text{vol}}}. \tag{4}$$

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.

Properties	Symbol	Value	Units
Atomic Number	Z	4	
Density	ρ	1.844	g·cm^{-3}
Tensile Strength	σ_τ	370	MPa
Yield Strength	σ_λ	240	MPa
Thermal Conductivity	κ	216	W·m^{-1}·K^{-1}
Quantities			
Height	h	1.0	m
Radius	r	10.00	mm
Area	A	314.159	mm^2
Strain	σ	28.968	kPa
Force	F	9.100	N

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

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

$$\sigma = \frac{1}{2}\rho v^2 + \rho g h + p, \tag{5}$$

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 point-pressure. However, as seen in Table II, the flow rate for the liquid Xenon is quite small. Additionally, p is relative, and we are only considering differences in pressure. Therefore, we can ignore the second order term and the point-pressure term to further simplify our approximation to

$$\sigma = \rho g h. \tag{6}$$

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

By varying the thickness of the Beryllium window, we can also vary the point at which the Beryllium will deform both plasticly and elasticly. This relationship is

$$\sum_{\substack{\text{don't look}}}^{\text{at me,}} \text{I'm just a placeholder} \tag{7}$$

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).