Liquid Xenon Positron Target

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Max Varverakis, Cal Poly
Spencer Gessner, SLAC
Robert Holtzapple, Cal Poly
Hiroki Fujii, Nishina Center

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SLAC NATIONAL ACCELERATOR LABORATORY

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Issues with Positron Production for Linear Colliders

Conventional Scheme
Direct high energy electrons (~10 GeV) into a high-Z target.

Target Requirements
1. High-Z
2. Short radiation length (≤$\mathcal{O}$(1 cm))
3. High energy deposition threshold

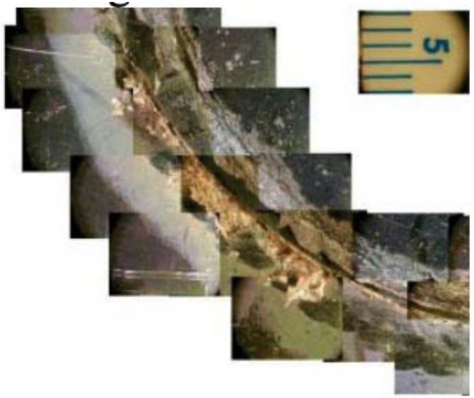
Established (Solid) Target Materials
1. Tantalum (Ta) with radiation length L_{RL} ~ 0.4094 cm.
2. Tungsten-Rhenium ($W_{75}Re_{25}$) alloy with radiation length L_{RL} ~ 0.3430 cm.

Problem
Producing positrons generates lots of thermal energy.
Future linear colliders require greater positron production rates ⇒ more heat!

Result
Solid targets degrade over time [1]
⇒ Solid targets have shortened operational lifespans.

This will become more apparent for future collider usage.

⇒ Current techniques may require additional measures to account for this



Degraded section of SLC positron target
ANALYSIS OF BEAM-INDUCED DAMAGE TO THE SLC POSITRON PRODUCTION TARGET | Fig 3b
https://accelconf.web.cern.ch/p01/PAPERS/WPAH019.PDF

Current Techniques to Mitigate Target Damage

Solid Targets

1. **Spin the target** to avoid the electron beam impinging on the same spot each beam pulse.

Problems: (i) Strict motor requirements. (ii) Induced eddy currents ⇒ large power requirements [2].

2. Integrate a (liquid) **cooling system** to maintain suitable target temperatures.

Problems: Difficulties arise when developing solid target cooling mechanisms (i.e., how to transport coolant to/from target without obstructing electron beam?)

Liquid Target Alternatives

Various liquid targets have been explored for use in the conventional positron production scheme, such as:

1. Mercury
2. Lead

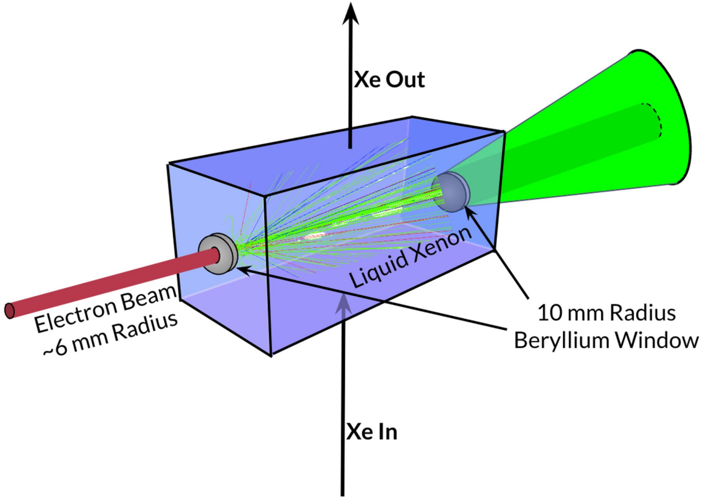
Problems: (i) Concerns about proper containment. (ii) These substances are **toxic** which further complicates effective usage.

Our Solution: Liquid Xenon

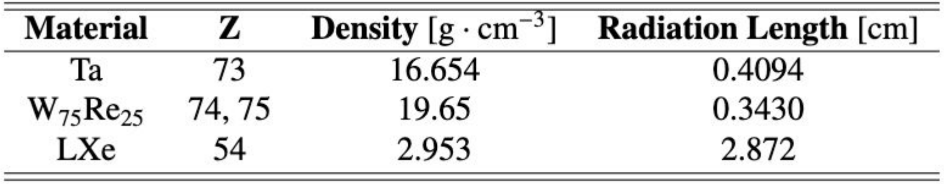
Use a **liquid xenon** (LXe) positron target!

Why?

1. Xenon is nonreactive (noble gas)
2. It's high-Z
3. Dense liquid at relatively high temperatures (~165 K)
4. LXe has a short radiation length (for a nonmetal)
5. LXe is non-toxic
6. High energy deposition threshold
7. LXe is continually refreshed and not susceptible to degradation
8. Cooling/recycling of LXe occurs away from IP
9. Positron yields are comparable with solid targets



Schematic of the liquid xenon (LXe) positron target setup. Electron beam enters from the left, passing through a beryllium window into the vessel of LXe. The resulting EM shower exits through an identical beryllium window.



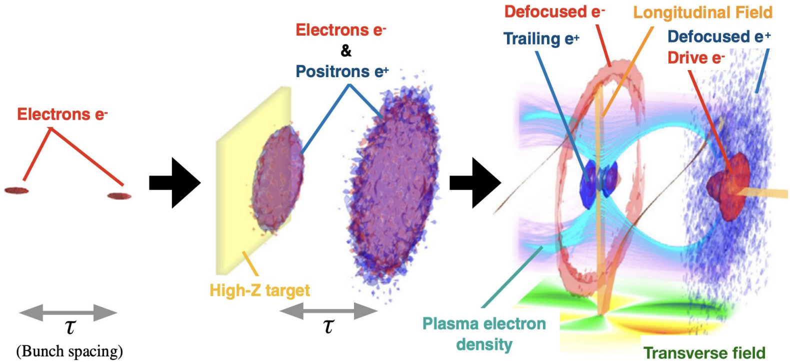
Material	Z	Density $[\mathrm{g} \cdot \mathrm{cm}^{-3}]$	Radiation Length [cm]
Ta	73	16.654	0.4094
$W_{75}Re_{25}$	74, 75	19.65	0.3430
LXe	54	2.953	2.872

Notable properties for various target materials [3, 4, 5].

GEANT4 Simulations of Positron Sources

We simulated positron production in **LXe**, **Ta**, and **$W_{75}Re_{25}$** targets using GEANT4 [6].

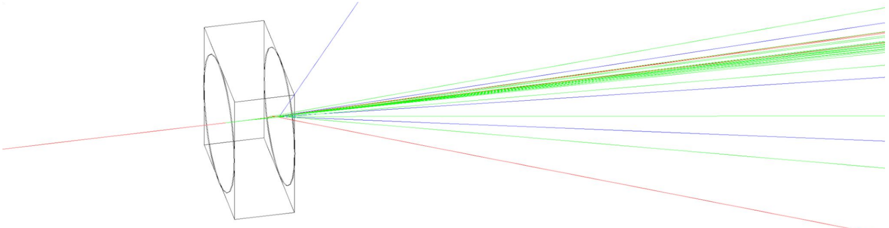
The simulation serves as a starting point for comparing LXe to well-established solid positron sources.



Fujii, et al., *Positron beam extraction from an electron-beam-driven plasma wakefield accelerator*, Phys. Rev. Accel. Beams, 22 (9) (2019), 10.1103/physrevaccelbeams.22.091301

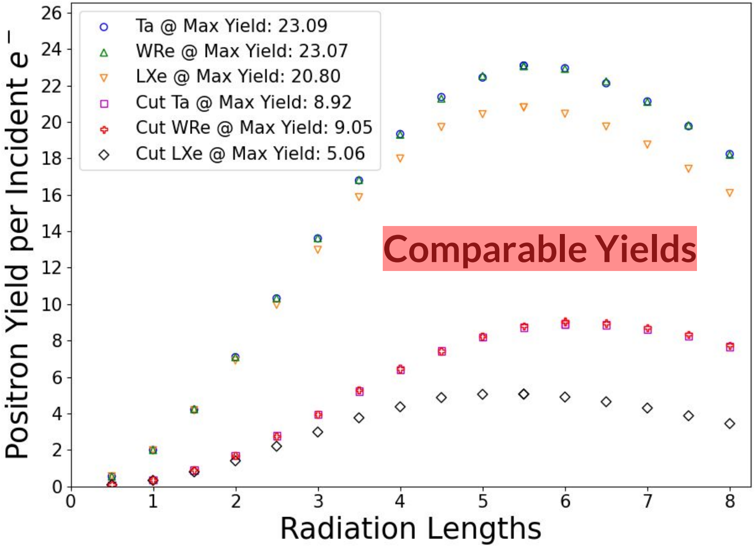
The simulation consisted of:

- **N_0= 10,000** macro particles onto the target
- Incoming beam spot size of **6 mm**
- **3 GeV**, **6 GeV,** and **10 GeV** beam energies
- Simulated over **0.5 to 8 radiation lengths** of each material
- **Particle selection criteria** were applied to replicate capture section losses



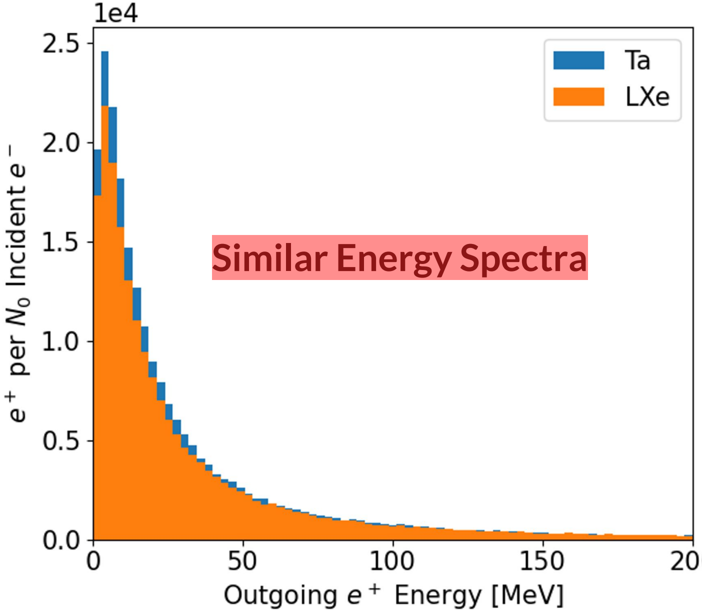
Single-particle EM shower generated in GEANT4. Red, blue, and green lines indicate e^-, e^+, and photon trajectories, respectively.

Comparing LXe to Ta and $W_{75}Re_{25}$



Incident electron beam energy: 10 GeV.

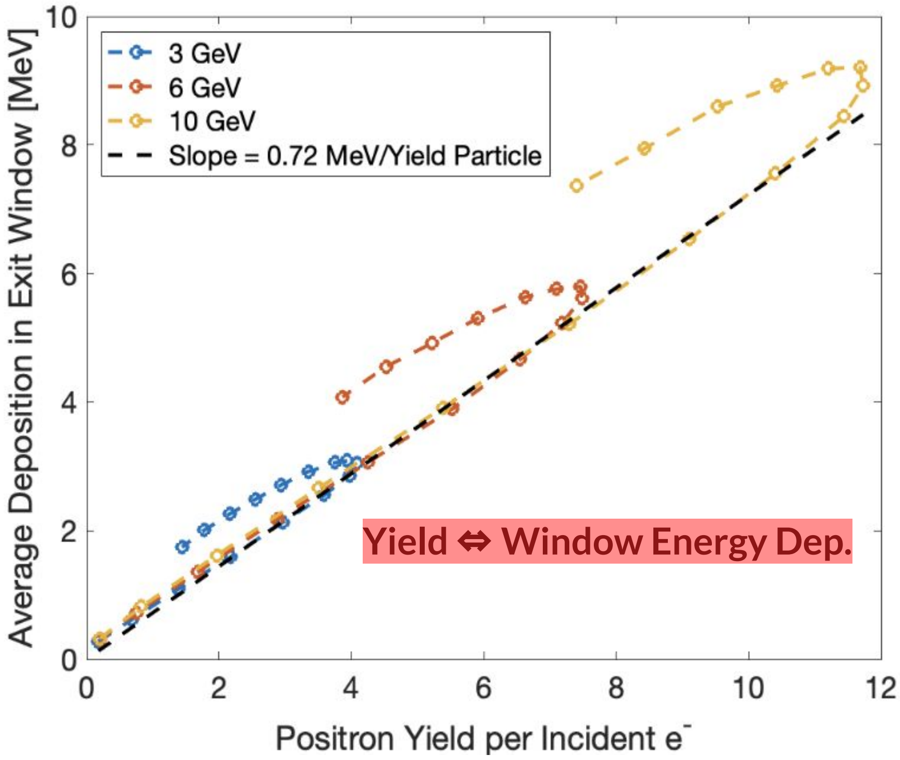
The cuts applied to the outgoing positrons require:
1. their energy is greater than 2 MeV and less than 22 MeV
2. a transverse offset less than 10 mm.



Energy spectrum of positrons generated in 5.5 radiation length LXe and Ta targets by a 10 GeV electron beam.

***We omit the $W_{75}Re_{25}$ spectrum because it closely matches the Ta spectrum.

Yield and Exit Window Energy Deposit Correlation



Energy deposition in the beryllium exit window as a function of particle yield for three different input electron beam energies.

***The yield value shown is after the particle selection cuts are applied.

There is a linear dependence on energy deposited in the exit window per yield particle up to the maximum yield for each incoming beam energy.

LXe Containment Considerations

Simulations show that beryllium disks are not suitable LXe windows for application at ILC-type colliders.

→ An alternative to beryllium windows must be determined.

<u>Main Design Constraints</u>

1. Containment vessel must withstand high pressures due to LXe vaporization (~300 kPa)
2. LXe must be able to flow through the vessel and evacuate vaporized xenon
3. The flow rate of LXe must be high enough to account for vaporization so that only fresh LXe interacts with the electron beam
4. Target chamber must endure sustained temperatures of ~165 K (LXe liquid temperature)
5. Electron beam and resulting EM shower must be able to enter/exit the chamber with minimal interaction (and energy deposition)

Next Steps

Future Work

- Where in the LXe is most of the energy deposited?

→ Additional GEANT4 simulations with more grid points will characterize the LXe volume.

- Does the LXe experience turbulence at certain flow rates?
- How does the vaporized xenon interact with the LXe?

→Computational fluid dynamic modeling of the LXe using ANSYS will help answer these questions.

Also: We plan to couple GEANT4 simulations to beam capture and transport models (e.g., GPT & ELEGANT) to fully simulate the target-to-damping ring design.

Unresolved Questions

- Is a LXe cryo-jet a possibility (no containment vessel at IP)?

- How does the cost of implementing/maintaining the LXe target compare to the replacement/maintenance costs of solid targets?

Conclusion

Liquid xenon is a promising candidate for use as a positron source in future linear collider application.

Why?

1. LXe is non-toxic

2. LXe has many appealing properties that make it relatively easy to work with (e.g., high-temp. liquid, nonreactive)

3. LXe has a short radiation length & high energy deposition threshold

4. LXe is not susceptible to long-term degradation

5. Positron output is similar to solid targets (comparable yields and energies)

Future work will elaborate on the findings of our simulations to build a better picture of the LXe target in action.

Acknowledgements/References

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

References

[1] V. Bharadwaj, et al., in PACS2001. Proceedings of the 2001 Particle Accelerator Conference (Cat. No.01CH37268), Vol. 3 (2001) pp. 2123–2125 vol.3.
[2] Simulations of the Rotating Positron Target in the Presence of OMD Field, S. Antipov, et al., DOI: 10.1109/PAC.2007.4440617
[3] Workman R.L., et al., Particle Data Group Collaboration, Rev. particle phys., PTEP, 2022 (2022), p. 083C01, 10.1093/ptep/ptac097
[4] Schultz D.C., Batygin Y.K., Bharadwaj V., Sheppard J.C., NLC positron target heating (2002)
[5] J.C. Liu, T. Kotseroglou, W.R. Nelson, D.C. Schultz, Polarization study for NLC positron source using EGS4, in: 2nd International Workshop on EGS4, 2000, pp. 115–123.
[6] S. Agostinelli et al. (GEANT4), Nucl. Instrum. Meth. A 506, 250 (2003).

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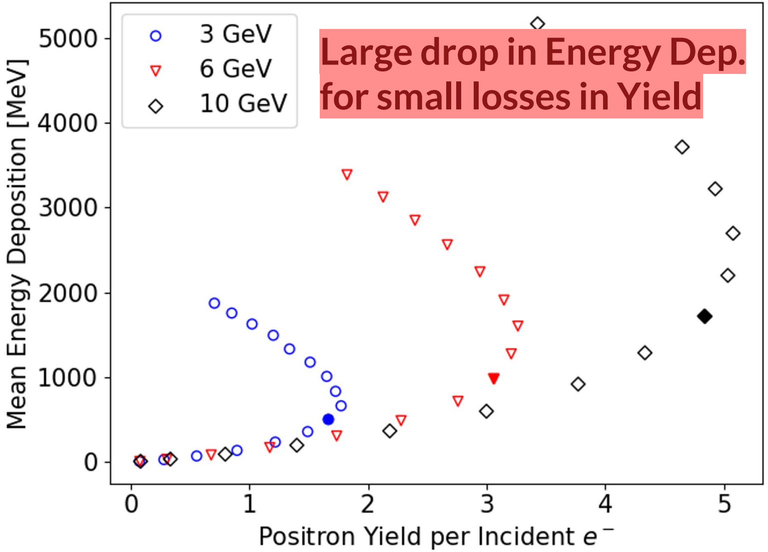
(Extra) LXe Energy Deposition Caveats



Large drop in Energy Dep. for small losses in Yield

Mean energy deposition in LXe target per incident electron as a function of positron yield at three different beam energies.

Each point represents a different radiation length of the LXe target.

(Filled-in points indicate operating radiation length for LXe)