

# Secondary sources from laser-driven particle accelerators: an optimisation methodology

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High-brightness photon and neutron sources are essential tools in materials science and security. Recent advancements in laser wakefield acceleration (LWFA) offer a pathway to highly compact, high-yield secondary sources. In the pump-depletion-dominated bubble regime [1], rapid laser depletion drives a strongly cavitated wakefield. The resulting massive self-injection generates high-charge ( $> 5$  nC) electron bunches with broad energy spectra extending to several hundred MeV. When these electrons strike a high-Z target, they generate an electromagnetic cascade producing bremsstrahlung photons and photoneutrons via Giant Dipole Resonance. Previously [2], our automated 2D optimization framework maximized these yields, justifying Tungsten converters using a simplified 140 MeV ideal electron beam (IEB) approximation. In this paper, we investigate whether this methodological simplification is a valid approximation for selecting both material and optimal thickness.

We evaluate secondary yields using the full, realistic electron spectrum from SMILEI PIC simulations, comparing results against the 140 MeV baseline, an IEB matching the spectrum's mean energy (156 MeV), and a systematic scan of higher-energy IEBs. We aim to determine if a broadband LWFA spectrum can be reliably approximated by its mean energy for target optimization.

The study employs a two-stage simulation workflow deployed on the KAROLINA supercomputer. First, the LWFA process is modeled via 3D PIC simulations in SMILEI, utilizing a 1.5 J, 6 fs laser pulse. The extracted

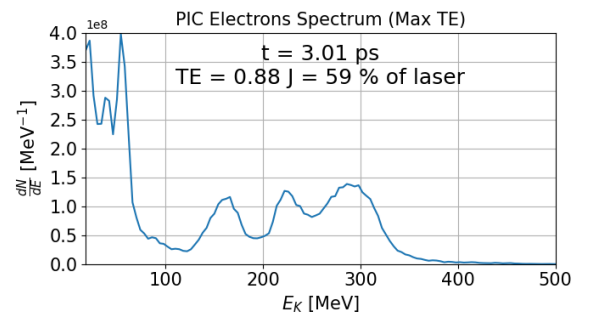


Figure 1: Electron energy spectrum extracted from the PIC simulation at  $t = 3$  ps corresponding to maximum total electron energy.

electron phase-space (filtered for  $P_x > 15.33$  MeV/c) serves as the source term. This actual spectrum, presented in Fig. 1, is broad and non-exponentially decaying. Notably, it contains a large population of electrons above 70 MeV—which leads to highly efficient bremsstrahlung production—alongside a prominent high-energy tail extending beyond 350 MeV, resulting in a mean energy of 156 MeV.

In the second stage, FLUKA Monte Carlo transport is used to model the electromagnetic cascade and photonuclear reactions within solid cylindrical converters. To systematically find the optimal converter length ( $L_c$ ) for various input spectra, we employed a 1D optimization loop utilizing SciPy’s `minimize_scalar` algorithm.

To efficiently navigate the inherent statistical noise of Monte Carlo simulations, we set the optimizer’s absolute convergence tolerance to  $\text{xatol} = 0.05$  cm. Because the neutron yield exhibits a broad, remarkably flat plateau near its optimum, the total yield barely changes with small variations in cylinder length. Consequently, any inherent Monte Carlo statistical fluctuation becomes highly significant relative to the local gradient, creating a noisy optimization landscape. This  $\text{xatol}$  value allows the algorithm to confidently identify the high-yield plateau without over-evaluating sub-millimeter statistical anomalies. Each FLUKA evaluation simulated a total number of  $1.28 \cdot 10^7$  primaries. The photon biasing LAM-BIAS card was set to 0.01 to artificially enhance photonuclear reaction sampling.

We first investigated whether the choice of the incident electron spectrum alters the fundamental material scaling for neutron production. Fig. 2(a) presents the peak neutron yields across various elements (from Fe to U) utilizing the original 140 MeV IEB, the 156 MeV IEB (mean spectral energy), and the full PIC spectrum.

The results confirm that the relative scaling of the monoenergetic yield perfectly mirrors the scaling of the full spectrum. The neutron conversion efficiency is fundamentally governed by the Z-enhanced bremsstrahlung production and the specific photonuclear cross-sections (GDR) of the material, establishing Tungsten (W) as a superior practical choice regardless of the exact

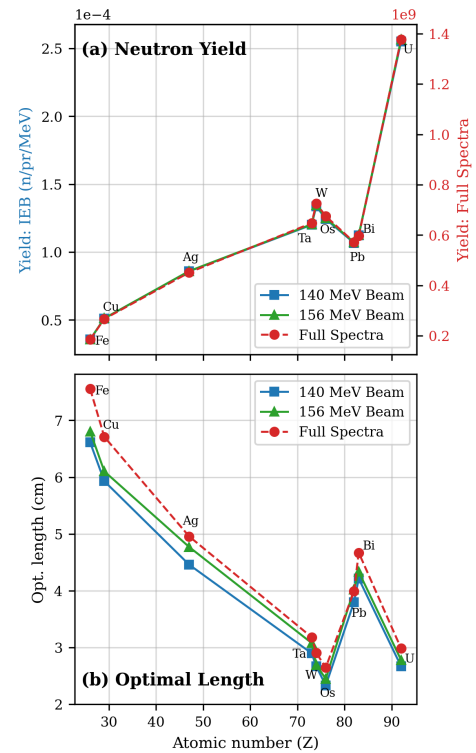


Figure 2: (a) Relative neutron yield scaling and (b) optimal converter thickness across various materials.

incident electron energy distribution.

However, as shown in Fig. 2(b), the optimal converter thickness diverges considerably. Crucially, optimizing based solely on the 156 MeV average energy leads to a slightly inaccurate prediction of the optimal length required for the full PIC spectrum. For all materials, the true optimal thickness is shifted deeper into the target.

To understand this discrepancy, we conducted a parameter scan using ideal electron beams ranging from 150 MeV to 500 MeV to identify which monoenergetic equivalent best matches the optimal thickness ( $L_c \approx 2.90 \pm 0.025$  cm for Tungsten) dictated by the actual spectrum. As depicted in Fig. 3(a), the optimal converter length seems to scale logarithmically with the incident electron energy. Our simulations confirm that an effective monoenergetic beam of 200 MeV to 250 MeV successfully recreates the cascade depth of the true spectrum.

This logarithmic behavior is governed by fundamental electromagnetic cascade mechanics. According to standard cosmic-ray and shower theory [3], the longitudinal center of gravity ( $\bar{t}$ ) and the depth of the shower maximum ( $t_{\max}$ ) scale proportionally to  $\ln(E_0/E_c)$ , where  $E_0$  is the primary energy and  $E_c$  is the critical energy of the target material. Because the energy division process within the cascade is exponential, the physical penetration depth required to reach the peak photon track length flattens at higher energies.

While the dense population of lower-energy electrons pulls the arithmetic average of the LWFA bunch down to 156 MeV, the high-energy electrons in the tail (extending beyond 350 MeV) are disproportionately more efficient at driving the cascade than sub 70 MeV electrons. Consequently, the optimal geometric thickness for neutron generation shifts deeper into the target, but at a heavily diminished, logarithmic rate as the effective energy of the spectrum increases. The “effective” energy required to model the target depth acts as a cross-section-weighted average, skewed toward the high-energy tail rather than the arithmetic mean.

Our findings demonstrate that the relative material scaling for neutron yield is effectively

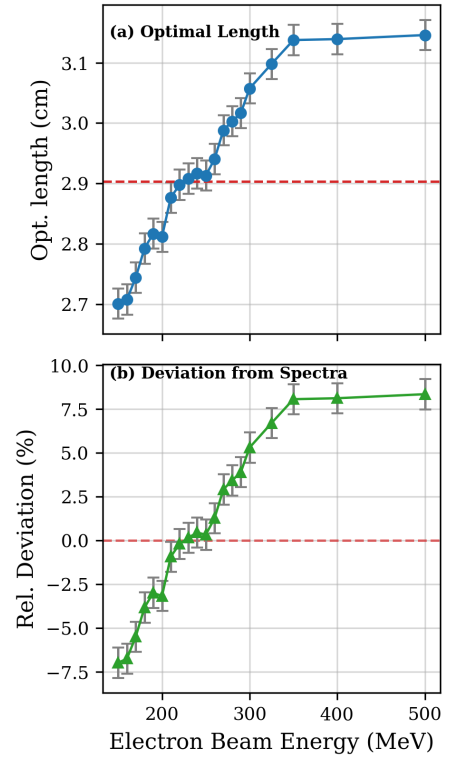


Figure 3: (a) Optimal Tungsten converter length as a function of electron beam energy. (b) Relative deviation of the optimum converter length from the full spectrum optimum.

independent of the incident electron energy distribution. Therefore, utilizing a simplified monoenergetic beam yields valid relative comparisons for selecting optimal converter materials. Furthermore, because the neutron yield exhibits a relatively broad plateau near the optimum, slight deviations in target geometry do not critically impact the overall yield. Nevertheless, relying solely on an arithmetic mean introduces systematic inaccuracies when predicting the exact physical target geometries. Methodologically, this indicates that rigorous start-to-end simulations coupling actual PIC phase-space directly into Monte Carlo frameworks remain necessary to precisely capture deep-cascade dynamics and extract absolute geometric optima. Finally, while neutron production is physically forgiving due to extensive target scattering, a similar geometry optimization study focused strictly on photon yield is necessary. Because photon production dictates a sharper geometric optimum, full-spectrum optimization will likely be more important and practically useful for designing high-brilliance LWFA-driven photon sources.

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