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HARNESSING MACHINE LEARNING FOR THE OPTIMAL DESIGN OF ILC E-DRIVEN POSITRON SOURCE

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Abstract

The International Linear Collider (ILC) is a next-generation electron-positron collider designed to operate at center-of-mass energies ranging from 250 GeV to 1 TeV, providing opportunities for exploring physics beyond the Standard Model. A critical component of the ILC is the E-driven positron source, which requires sophisticated technology to produce large quantities of positrons. Traditional accelerator design methods involve sequential optimization, which is inefficient and challenging for achieving global optimization. This study introduced the use of the Tree-structured Parzen Estimator (TPE) algorithm, a black-box optimization method, to improve the design efficiency of the ILC E-driven positron source. By implementing the TPE algorithm using Optuna, we optimized up to 8 parameters, achieving a positron capture efficiency of 1.42, significantly higher than the 1.20 efficiency obtained through manual optimization. This substantial improvement is expected to meet the safety standards for target destruction. The optimization process was also expedited, reducing the time from about a week to approximately half a day. These results demonstrate the potential of machine learning techniques in accelerator design, offering a more comprehensive global optimization by exploring a broader parameter space and avoiding local minima.

INTRODUCTION

The International Linear Collider (ILC) is a next-generation electron-positron collider designed to operate at center-of-mass energies ranging from 250 GeV to 1 TeV, opening up a wide range of possibilities for exploring physics beyond the Standard Model. As a linear accelerator, the ILC requires sophisticated technology to produce large quantities of positrons to accumulate the necessary statistics for experiments. The ILC E-driven positron source [1] is currently being designed and optimized using software tools such as Geant4, GPT, and SAD.

Traditionally, the design of accelerators has involved sequential optimization, where human judgment is used to interpret the results of physical simulations, followed by grid searches of a few parameters or optimizations based on experience. This process is repeated iteratively, making it inefficient and challenging to achieve global optimization, as even small design changes necessitate numerous processes.

Our group has recently begun incorporating machine learning techniques into the optimization process, experimenting with surrogate models using neural networks and optimization using genetic algorithms to improve design efficiency. In this paper, we report on the optimization and efficiency improvement of the ILC E-driven positron source using the Tree-structured Parzen Estimator (TPE) algorithm, a method of black-box optimization.

ILC E-DRIVEN POSITRON SOURCE SIMULATION

The schematic layout of the ILC electron-driven positron source is shown in Fig. 1. Geant4 [2] is used for simulating the initial production and capture of positrons at the target. GPT (General Particle Tracer) [3] models the transport and focusing of positrons from immediately after the target to the exit of the capture linac. SAD (Strategic Accelerator Design) [4] simulates the downstream sections, including from the exit of the capture linac to the ECS exit.

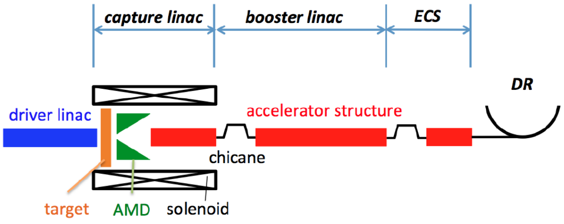

Figure 1: Schematic layout of the ILC E-driven positron source [5].

The primary performance metric for the positron source simulation is the positron capture efficiency, denoted as η. This efficiency is defined as the ratio of the number of positrons (N_{e^+}) that meet the damping ring acceptance at the ECS exit to the number of electrons (N_{e^-}) incident on the target, i.e., $\eta = \frac{N_{e^+}}{N_{e^-}}$.

While positron capture efficiency is a crucial metric, a challenging aspect of optimization is that even minor parameter changes can significantly alter the trajectories, often resulting in a drastic reduction of positrons at the exit and a capture efficiency of zero.

OPTIMIZATION METHODOLOGY

Due to the high computational cost associated with high-fidelity simulations of the positron source, traditional approaches have often involved trade-offs between computational load and simulation accuracy by adjusting time steps or excluding certain physical effects. To achieve a highly accurate accelerator design with minimal simulation runs, efficient optimization is crucial. Given the complexity of the accelerator, deriving desired information such as phase space distribution and positron capture efficiency from simple physical models is impractical. Therefore, black-box optimization (BBO), which does not require knowledge of the objective function's form, is well-suited for this task.

Based on preliminary trials and literature, we determined that the Tree-structured Parzen Estimator (TPE) algorithm [6] is promising for our needs, considering its capability to handle large computational loads and numerous parameters. Although we briefly experimented with other BBO algorithms and hyperparameter adjustments, TPE consistently demonstrated stable and rapid convergence for our application.

We implemented the TPE algorithm using Optuna [6] and its 'TPESampler'. Our optimization focused on the section from the chicane at the capture linac exit to the ECS exit, simulated using SAD. The upstream GPT simulations, which require significant computational resources due to iterative runs needed for accurate beam loading compensation, were excluded from this optimization.

The simulations and optimizations were conducted on a standard desktop computer available in our laboratory (Intel(R) Core(TM) i7-10700 CPU @ 2.90GHzIntel(R) Core(TM) i7-10700 CPU @ 2.90GHz, 8 cores, and 16 logical processors., 8 cores, and 16 logical processors.), without the use of specialized HPC resources. We utilized 15 out of 16 logical threads for parallelization.

Initially, we started with 3–4 parameters and gradually increased to a maximum of 8 parameters, which included the entrance momentum at the first chicane, chicane bending angle, Booster initial phase, Booster peak voltage, ECS initial phase, ECS peak voltage, ECS chicane bending angle, and the z-center of the damping ring. These parameters were constrained to realistic accelerator values, which helped expedite the optimization process by narrowing the parameter space.

RESULTS AND DISCUSSION

Optimization Results

The optimization process using the Tree-structured Parzen Estimator (TPE) algorithm was conducted with up to 8 parameters. The history plot of the optimization process is shown in Fig. 2. The optimized positron capture efficiency (η) achieved was 1.42, which is significantly higher than the 1.20 efficiency obtained through manual optimization.

To further understand the relationship between the optimization parameters and the number of captured positrons, a slice plot is presented in Fig. 3. This plot illustrates the exploration of the parameter space over the course of the trials, highlighting the regions where the optimal solutions are likely to be found. It provides insight into which parameter ranges are most influential in achieving higher positron capture efficiency.

Comparison with Traditional Methods

The improvement in positron capture efficiency using the TPE-based optimization method over manual optimization can be attributed to several factors. Firstly, the TPE algorithm enabled a more comprehensive global optimization, exploring a broader parameter space and avoiding the local minima that manual optimization often falls into.

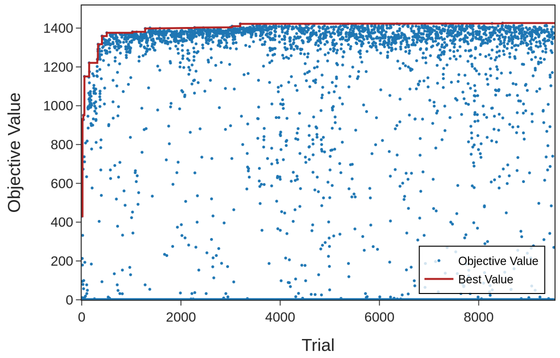

Figure 2: The history plot of the optimization process using the TPE algorithm with 8 parameters. The x-axis represents the number of trials, and the y-axis represents the number of captured positrons. It took approximately 380 minutes to complete 4000 trials.

In terms of optimization time, the TPE-based method demonstrated a substantial improvement. Manual optimization usually takes about a week to complete, whereas the TPE-based method reduced this time to approximately half a day. This significant reduction in optimization time highlights the efficiency and practicality of the TPE algorithm for complex accelerator design problems.

Computation Time

The computation time for each simulation was carefully monitored. The table summarizing the simulation times for both completed and timed-out runs is presented in Table 1, which shows the time per trial. To ensure the optimization process continued smoothly despite occasional issues where the simulation would not terminate, a timeout was set. By increasing the thread count to 15, the process was accelerated by nearly 10 times compared to using a single thread.

Table 1: Computation Times and Speedup Factors for Different Thread Counts

Threads	Time (s/trial)	Speedup
1	57.8	-
15	5.79	9.98x

CONCLUSIONS AND FUTURE WORK

In this study, we have demonstrated the effectiveness of the Tree-structured Parzen Estimator (TPE) algorithm for optimizing the ILC E-driven positron source. By leveraging the TPE algorithm, we achieved a positron capture efficiency of 1.42, which is significantly higher than the 1.20 efficiency obtained through manual optimization. The optimization

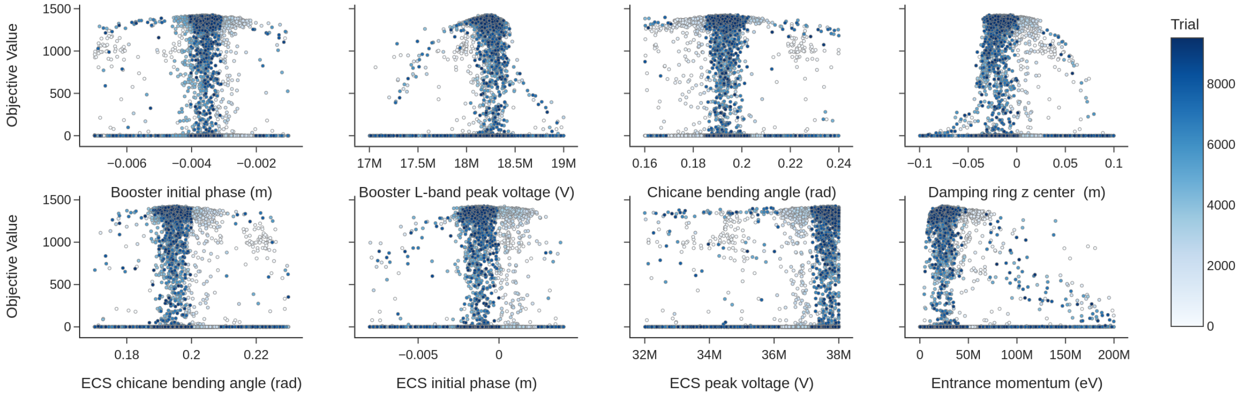

Figure 3: Slice plot showing the relationship between optimization parameters and the number of captured positrons. The x-axis represents the parameter values, and the y-axis represents the number of captured positrons. The color gradient indicates the trial number, with darker colors representing later trials.

process was also considerably expedited, reducing the time from about a week to approximately half a day.

The results indicate that the TPE algorithm provides a more comprehensive global optimization by exploring a broader parameter space and avoiding local minima. This approach not only improves the efficiency of the positron source but also highlights the potential of machine learning techniques in accelerator design.

Future work will focus on several key areas to further enhance the optimization process. One important direction is the utilization of High-Performance Computing (HPC) resources, which could provide a notable improvement in the optimization process compared to standard desktop computers.

Additionally, while this study focused on optimizing representative parameters typically adjusted manually, there is potential for machine learning to handle a much larger set of parameters. This includes fine-tuning individual components such as each accelerating structure or other detailed parameters. Achieving global optimization with a vast number of parameters remains a challenging but promising area for future research.

Another future objective is to extend the optimization to cover the entire ILC E-driven positron source, including the Capture Linac. Automating the start-to-end optimization of the positron source will ensure a more integrated and efficient design process.

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