MEDICAL PHYSICS COMMUNITY
INSPIRATION INNOVATION IMPACT
2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

Multi-Objective Genetic Optimization of a 10 MeV Small-Animal Irradiator for X-Ray FLASH

Stanford MEDICINE | Biomedical Physics

Mindy Harkness[1] · Brendan Whelan, PhD[2] · Billy W. Loo Jr., MD, PhD[1]

[1]Department of Radiation Oncology, Stanford University, Stanford, CA [2]SeeTreat Medical, Sydney, Australia

ABSTRACT

Radiation therapy optimization problems frequently involve multiple competing objectives, making multi-objective optimization an important tool for navigating trade-offs. This work integrated a **Non-Dominated Sorting Genetic Algorithm (NSGA-II)**[1] optimizer with **TOPAS Monte Carlo (MC)**[3] simulations to identify optimal geometries for a simple 10 MeV X-ray FLASH small-animal beamline.

A 10 MeV electron source with an X-ray conversion target, electron filter, and divergent tungsten collimator was simulated in TOPAS MC. Five geometric parameters were optimized: tungsten target thickness, copper electron filter thickness, SSD, collimator position, and collimator aperture size. Multi-objective optimization was performed using **TopasMOO, an open-source Python package extending TopasOpt,**[2] implementing the NSGA-II algorithm. Three objective functions were simultaneously evaluated: maximizing dose rate at d_{max}, minimizing the surface-to-d_{max} ratio to minimize electron contamination, and minimizing deviation from the desired field size.

The optimization was run for 50 generations with a population size of 20 for a total of 1,000 evaluations requiring 544 core-hours. The final Pareto front contained **25 solutions** with a final hypervolume size of 6.98x10³. Design dose rates ranged from **52.9 to 125 Gy/mAs**. Surface dose percentages ranged from **9.1% to 30.7%**. Field size deviation ranged from **0 to 19.4 mm**.

Integrating NSGA-II with TOPAS MC via TopasMOO enabled systematic exploration of design trade-offs in a small-animal irradiator.

CONTACT

Mindy Harkness

Department of Radiation Oncology
Stanford University, Stanford, CA

mharkness@stanford.edu

github.com/mindyharkness

INTRODUCTION

Implementing multi-objective optimization allows design trade-offs in radiation therapy optimization problems to be properly evaluated and visualized. We developed **TopasMOO**, an **open-source Python package** that allows for the optimization of **TOPAS MC³** simulations for multiple objectives. In X-ray FLASH beamline design, the competing demands of maximizing dose rate while minimizing surface dose and field leakage to create a useful field cannot be reconciled by manually tuning parameters in isolation, motivating a multi-objective, Monte Carlo–driven optimization. We demonstrated the capabilities of TopasMOO by optimizing a 10 MeV X-ray FLASH small-animal irradiator beamline using the **Non-Dominated Sorting Genetic Algorithm (NSGA-II)¹** algorithm.

METHODS & MATERIALS

TOPASMOO

To integrate multi-objective optimization with TOPAS MC, we developed TopasMOO, an open-source Python package extending TopasOpt[2] for multiple objectives. NSGA-II's population-based approach enables robust optimization with noisy Monte Carlo results, allowing lower-statistic simulations for faster optimization evaluations.

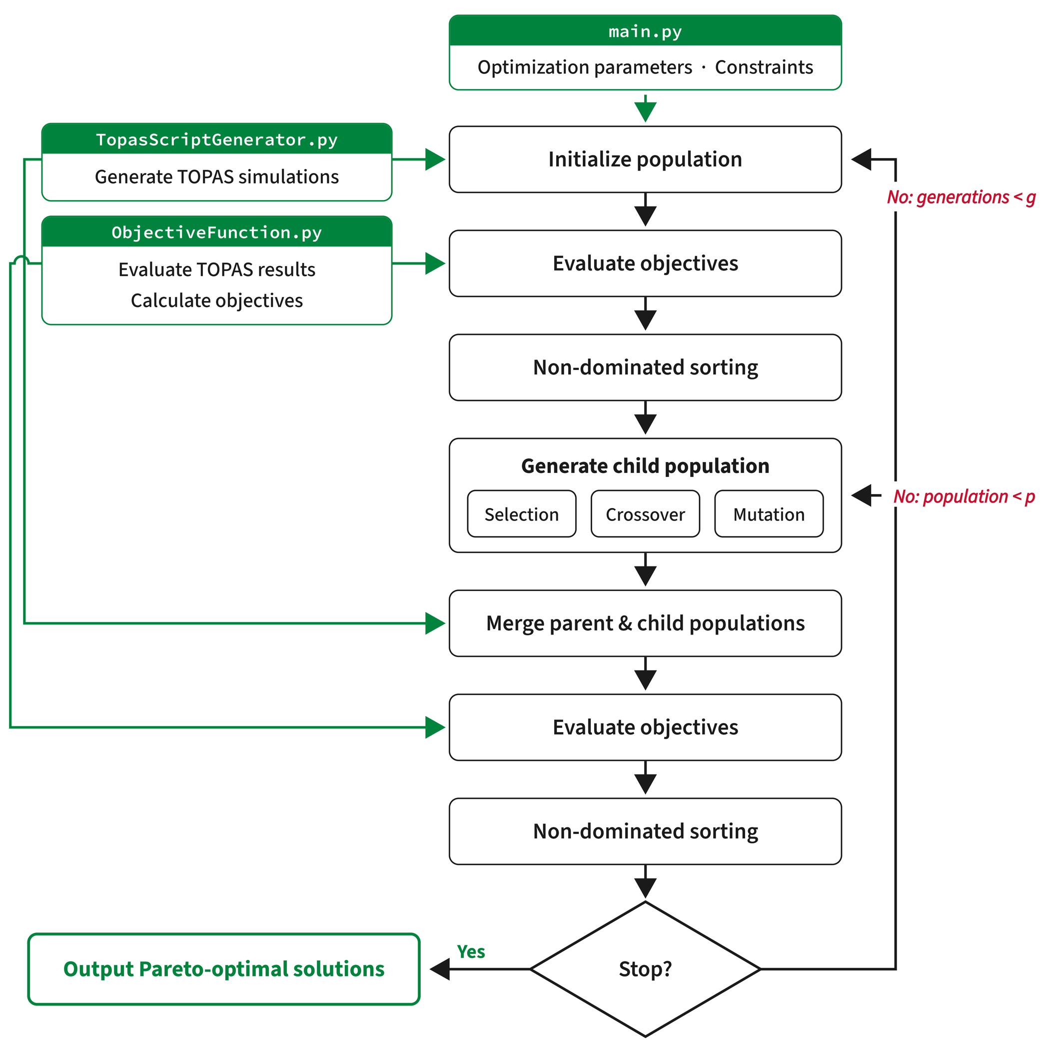

Figure 1. TopasMOO optimization workflow integrating NSGA-II with TOPAS Monte Carlo.

BEAMLINE OPTIMIZATION

A 10 MeV electron source with an X-ray conversion target, electron filter, and divergent tungsten collimator was simulated in TOPAS Monte Carlo (MC) to generate a 2x2 cm² field at source-to-surface distance (SSD). Dose was scored in a 6x6 cm² water phantom at SSD with 0.1 mm binning. Each run had two stages: transport to a phase-space scorer at the tank surface (2x10⁶ histories, 100x bremsstrahlung splitting in the target) and a water-tank simulation with 10 phase-space re-uses. Five geometric parameters were optimized according to three objective functions.

OPTIMIZED PARAMETERS

- **W target thickness**
- **Source-to-surface distance**
- **Cu filter thickness**
- **Collimator distance**
- **Collimator aperture size**

OBJECTIVE FUNCTIONS

- **Maximize dose rate at d_{max}**
- **Minimize surface-to-d_{max} dose ratio**
- **Minimize field-size deviation**

RESULTS

The optimization was run for **50 generations** with a **population size of 20** for a total of **1,000 evaluations**, requiring **544 core-hours**. The final Pareto front contained **25 solutions** with a final raw hypervolume size of 6.98×10³ (0.923 normalized). See below for the optimized setup with Pareto-optimal parameter ranges and objective value ranges.

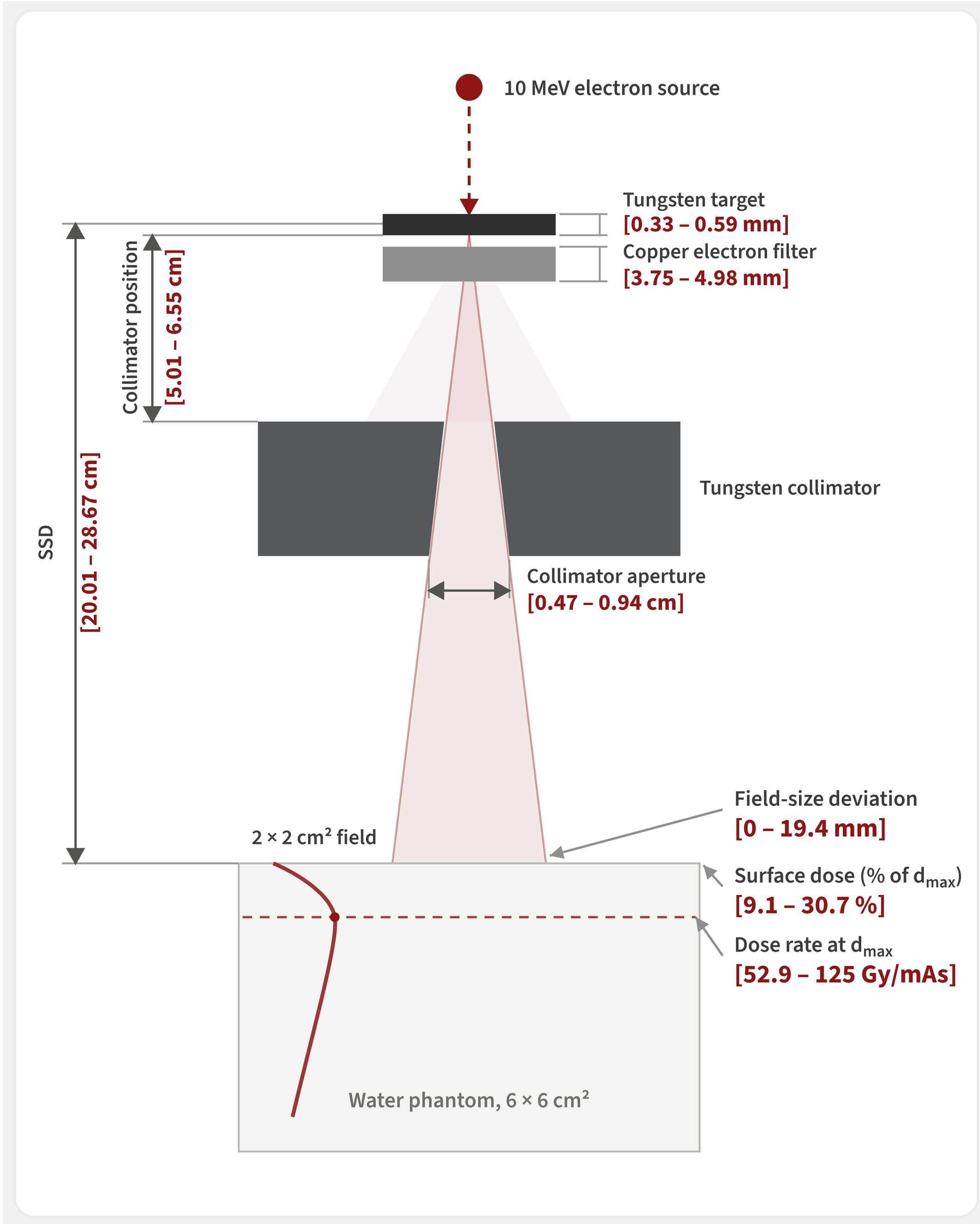

Figure 2. Optimized 10 MeV X-ray beamline geometry with Pareto-front parameter and objective function value ranges from the NSGA-II optimization.

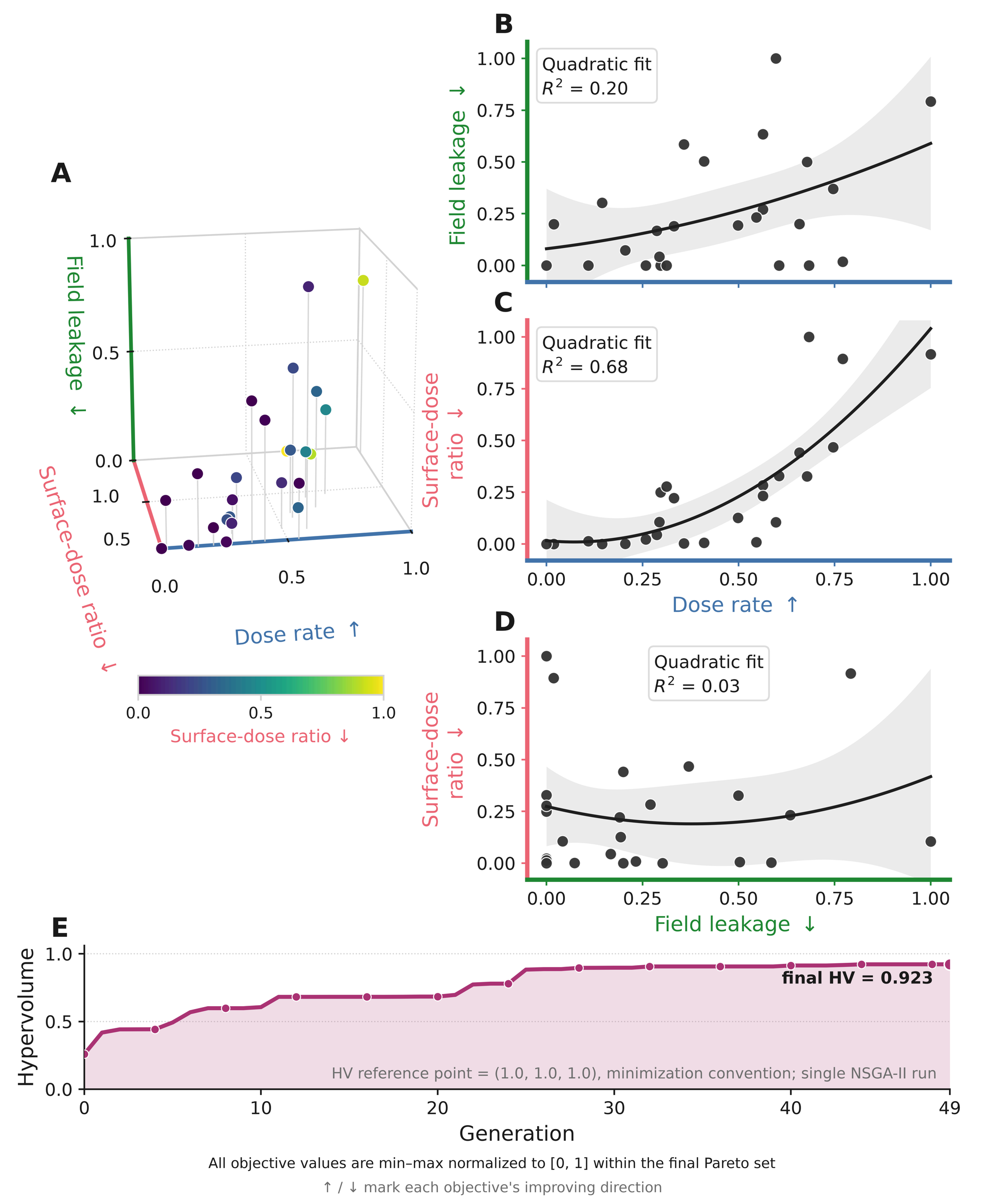

Figure 3. A) 3D Pareto front displaying all 25 optimal solutions in normalized objective space. B-D) Pairwise correlation of solutions based on normalized objective functions. A quadratic fit is displayed in black with a shaded 95% confidence band. E) Cumulative normalized hypervolume (the fraction of the normalized objective cube dominated by the best Pareto front found through each generation) over 50 optimization generations.

DISCUSSION

TopasMOO allowed for the multi-objective optimization of a 10 MeV x-ray small-animal irradiator for preclinical FLASH experiments, generating a **25-solution Pareto front**. A final design can be chosen from the Pareto front based on experimental priorities and constraints.

This optimization also reveals the interdependency of the three objectives: field leakage, surface-dose ratio, and dose rate. The most significant correlation was between surface-dose ratio and dose rate. This makes physical sense, as reduced electron filtration ought to yield a higher dose rate, at the cost of greater electron contamination. The correlation between field leakage and dose rate is also physically motivated, as tighter collimation blocks more of the generated photon fluence to shape a smaller field. There was no correlation between surface-dose ratio and field leakage.

While TopasMOO provides a set of Pareto-optimal solutions, a decision-making method is still needed to select a single design. One common approach is to select the "knee point": the solution on the Pareto front where the tradeoff between objectives is most balanced, so that moving further in either direction yields a small gain at a disproportionately large cost.[4]

TopasMOO currently implements only the NSGA-II algorithm. Additional algorithms such as Multi-objective Bayesian Optimization (MOBO) will be incorporated in future work.

CONCLUSIONS

Integrating NSGA-II with TOPAS MC via TopasMOO enabled systematic exploration of design trade-offs in a small-animal irradiator. Identifying a family of Pareto-optimal geometries enables informed decision-making, allowing the design to be tailored to address specific experimental and engineering constraints.

REFERENCES

1. Deb K, et al. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans Evol Comput.* 2002;6:182–197.
2. Whelan B, et al. TopasOpt: an open-source library for optimization with TOPAS Monte Carlo. *Phys Med Biol.* 2023.
3. Perl J, et al. TOPAS: an innovative proton Monte Carlo platform. *Med Phys.* 2012;39:6818–6837.
4. Deb K, Gupta S. Understanding knee points in bicriteria problems and their implications as preferred solution principles. *Eng Optim.* 2011;43(11):1175–1204.