LEIR: Optimizations with ML

Borja Rodriguez Mateos

BE-CSS, BE-ABP, SY-BI

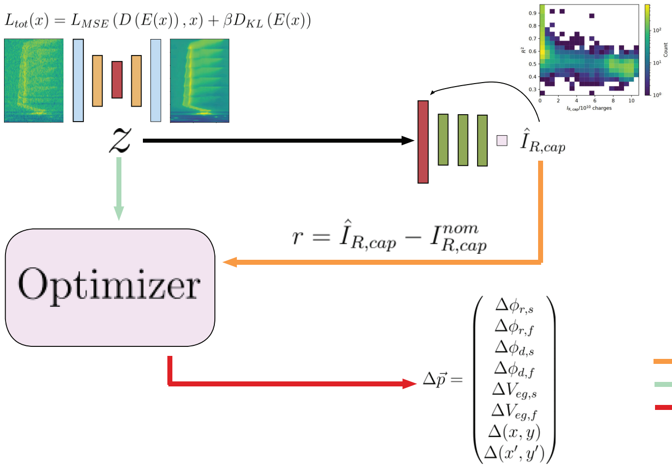
February 4, 2025

Acknowledgements: Theodoros Argyropoulos, Foteini Asvesta, Diogo Alves, Felix Carlier, Verena Kain, Nico Madysa, Nicolas Mounet, Michael Schenk, Maciej Slupecki

Challenges of LEIR injection

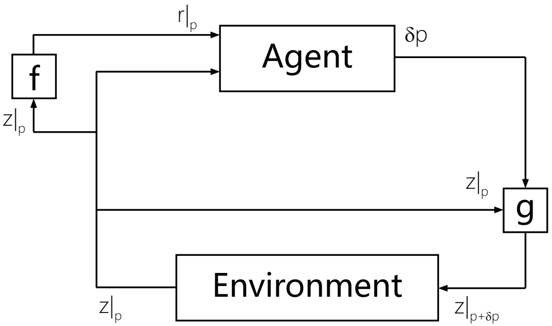
- Injection efficiency into LEIR severely depends on energy distribution of the incoming pulses from LINAC3
  - Accumulation of several pulses with multi turn injection using 6D phase-space painting
  - Cool and drag in momentum space the beam already circulating in LEIR
- Stripping foil has a limited lifespan and degrades over time
  - Impacts the mean ion energy and changes the energy distribution width
  - Decreases the injection efficiency over time and needs to be compensated manually
- We aim to develop both stateful and black-box optimizers for maintaining desired intensity in LEIR

Stateful optimization of injected beam intensity



- Training a VAE of longitudinal schottky spectra to obtain encoded latent vector **z**
- Optimizer observes encoding of schottky spectra **z** and intensity reading from the BCT
- Optimizer modifies relevant parameters for improving the intensity

Offline training of an RL agent on the surrogate model



Two models are used for the training :

- Reward model : $f(\mathbf{z}|_\mathbf{p}) = r|_\mathbf{p}$
- Transition model : $g(\mathbf{z}|_\mathbf{p}, \delta\mathbf{p}) = \mathbf{z}|_{\mathbf{p}+\delta\mathbf{p}}$

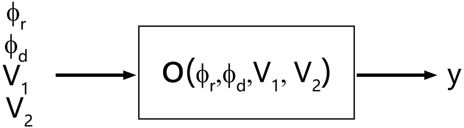
Loss used for training transition model:

$$
\begin{aligned}
L = & ||g(\mathbf{z}|_\mathbf{p}, \delta p) - \mathbf{z}|_{\mathbf{p}+\delta\mathbf{p}})|| \\
& + \gamma_1 ||g(g(\mathbf{z}|_\mathbf{p}, \delta p), -\delta p) - \mathbf{z}|_\mathbf{p}|| \\
& + \gamma_2 ||g(\mathbf{z}|_{\mathbf{p}+\delta\mathbf{p}}, -\delta p) - \mathbf{z}|_\mathbf{p}|| \\
& + \gamma_3 ||g(\mathbf{z}|_\mathbf{p}, 0) - \mathbf{z}|_\mathbf{p}|| \\
& + \gamma_4 ||g(\mathbf{z}|_{\mathbf{p}+\delta\mathbf{p}}, 0) - \mathbf{z}|_{\mathbf{p}+\delta\mathbf{p}}||
\end{aligned}
$$

→ Still needs to be tested online and evaluate quality of simulation-to-reality transfer

Black-box optimization of LEIR intensity (1)

Goal: Maximize or minimize objective function



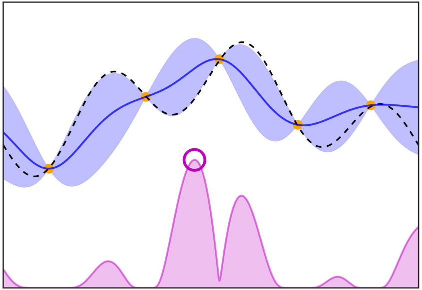
- Black box (no closed form, no gradients)
- Non-convex and multi-modal
- Noisy measurements ($\epsilon \sim \mathcal{N}(0, 0.1)$)
- Expensive evaluations (limited number of cycles)

Local optimization tools not suitable:

- Often requires gradients
- Easily get trapped in local minima for high dimensional problems
- Not graceful when handling measurement noise
- Not sample efficient enough

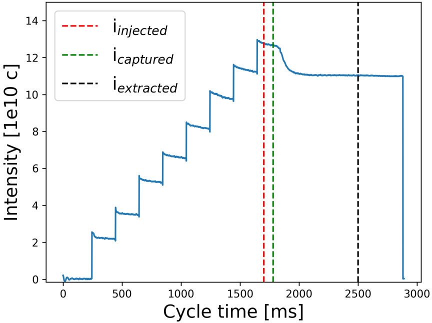
Black-box optimization of LEIR intensity (2)

Toy maximization example of Bayesian Optimization in 1D with 5 data points:



- Build a probabilistic proxy model for the objective using outcomes of past experiments as training data
- Optimize cheap proxy function to determine where to evaluate the true objective next
- Standard proxy: Gaussian process

Intensity optimization in LEIR ring

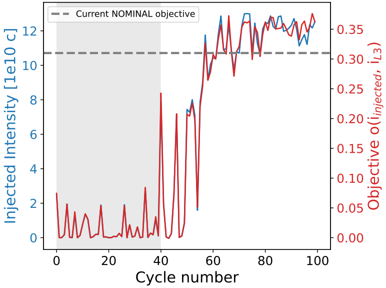


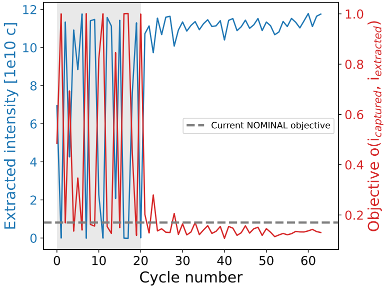
Maximizing objective:

$$o(i_{injected}, i_{L3}) = \frac{i_{injected}}{i_{L3}} = \frac{i_{injected}}{\sum_{j=1}^{8} i_j}$$

Minimizing objective:

$$o(i_{captured}, i_{extracted}) = \frac{i_{captured} - i_{extracted}}{i_{captured}}$$

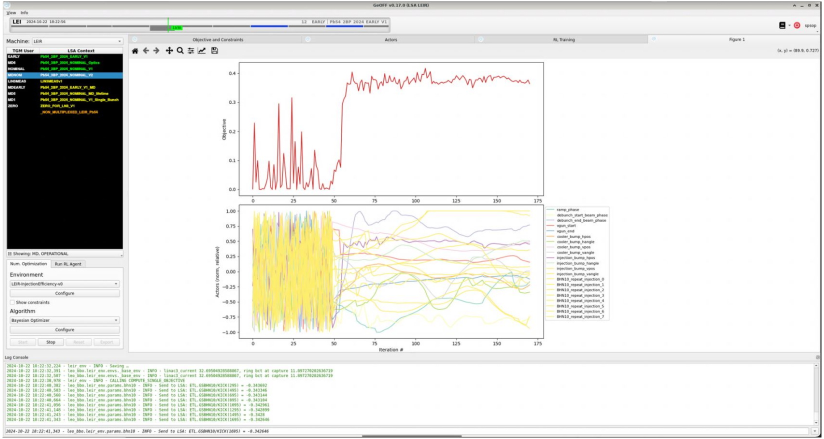




- Objective function modeled by Gaussian Process
- Used acquisition function $a_{\mathrm{UCB}}(x;\beta) = \mu(x) + \sqrt{\beta}\sigma(x)$
- 10 initial samples with Sobol sequence and 10 with $a_{\mathrm{PE}}(x) = \sigma(x)$

- Injection optimization changing Ramping and Debunching cavity phases, cooler and injection bump, e-gun voltage and BHN10
- Capture optimization changing f_{rev}, e-gun voltage, sextupole and skew sextupole current

Operational Black-box optimization with GeoFF support



- Build the black-box optimizers to be used with GeoFF operationally
- Works both for injection and RF capture optimization

2024 data collection

- Recorded all optimization and exploration cycles in 2024 making up to $\approx$ 40'000 injections with high variety of stripping foil age (Making $\approx$ 50'000 samples with 2023 run).
- Recorded both EARLY and NOMINAL cycles.
- Used full possible range of parameters in both exploration and optimization runs.
- Large quantities of data enables pre-training of larger and more complex models in the future.

2025 Planning

- Stateful and black-box optimization during oxygen run on parallel MD cycle. Might prioritize black-box due to longer cooling times. (Week 20-24 depending on beam commissioning)
- Stateful and black-box optimization during lead run on parallel MD cycle. Having a stateful autopilot running constantly on a separate cycle for assisting optimization on NOMINAL cycle (Week 36-50)
- Test Multi-Objective Bayesian Optimization to optimize both injected intensity and RF capture at the same time.
- Test functional Bayesian Optimization in Oxygen and Lead run.

Thank you for your attention

References

Biancacci. "Advancements in injection efficiency modelling for the Low Energy Ion Ring (LEIR) at CERN". In: *JACoW IPAC* 2023 (2023), MOPL016. DOI: 10.18429/JACoW-IPAC2023-MOPL016.

Madysa. "Automated Intensity Optimisation Using Reinforcement Learning at LEIR". In: *JACoW IPAC* 2022 (2022), pp. 941–944. DOI: 10.18429/JACoW-IPAC2022-TUPOST040.