4-2022

Lattice Optics Optimization for Recirculatory Energy Recovery Linacs with Multi-Objective Optimization

Isurumali Neththikumara
Old Dominion University

Todd Satogata
Thomas Jefferson National Accelerator Facility

Alex Bogacz
Thomas Jefferson National Accelerator Facility

Ryan Bodenstein
Thomas Jefferson National Accelerator Facility

Arthur Vandenhoeke
Artificial Intelligence Lab, Brussels

Lattice Optics Optimization for Recirculatory Energy Recovery Linacs with Multi-Objective Optimization*

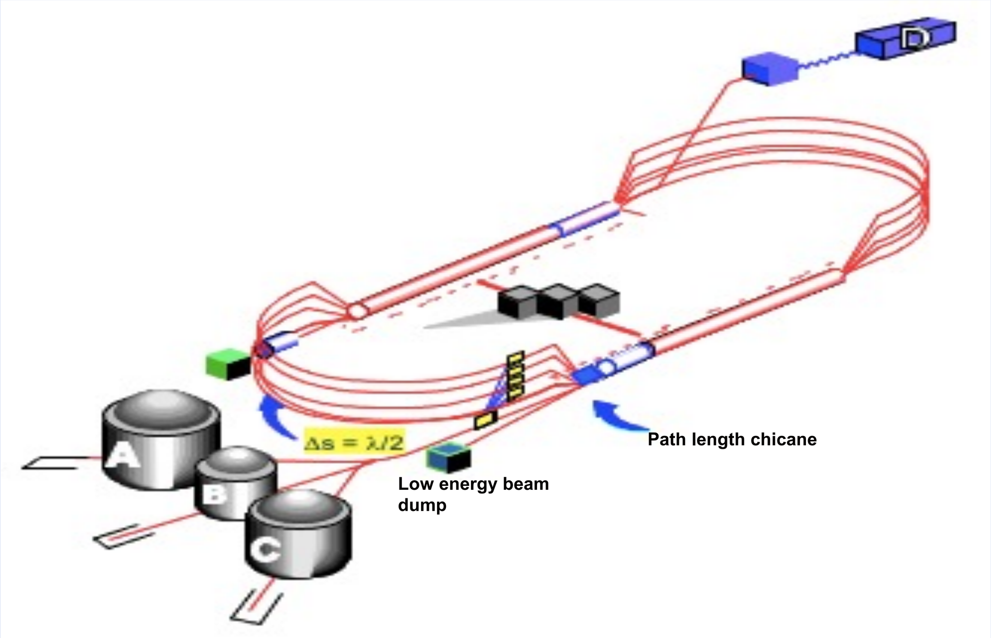
I. Neththikumara[1 #], T. Satogata[1,2], A. Bogacz[2], R. Bodenstein[2], A. Vandenhoeke[3]
[1] *Center For Accelerator Studies, Old Dominion University, Norfolk, VA 23529, U.S.A.*
[2] *Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, U.S.A.*
[3] *Artificial Intelligence Lab, 1050 Brussels, Belgium*

ABSTRACT

Beamline optics design for recirculating linear accelerators requires special attention to suppress beam instabilities arising due to collective effects. The impact of these collective effects become more pronounced with the addition of energy recovery (ER) capability. Jefferson Lab's multipass, multi-GeV ER proposal for the CEBAF accelerator, ER@CEBAF, is a 10-pass ER demonstration with low beam current. Tighter control of the beam parameters at lower energies is necessary to avoid beam break-up instabilities, even with a small beam current. Optics optimizations require balancing both beta excursions at high-energy passes and overfocusing at low-energy passes. Here, we discuss an optics optimization process for recirculating energy-recovering linacs (ERLs) using multi-objective evolutionary search methods.

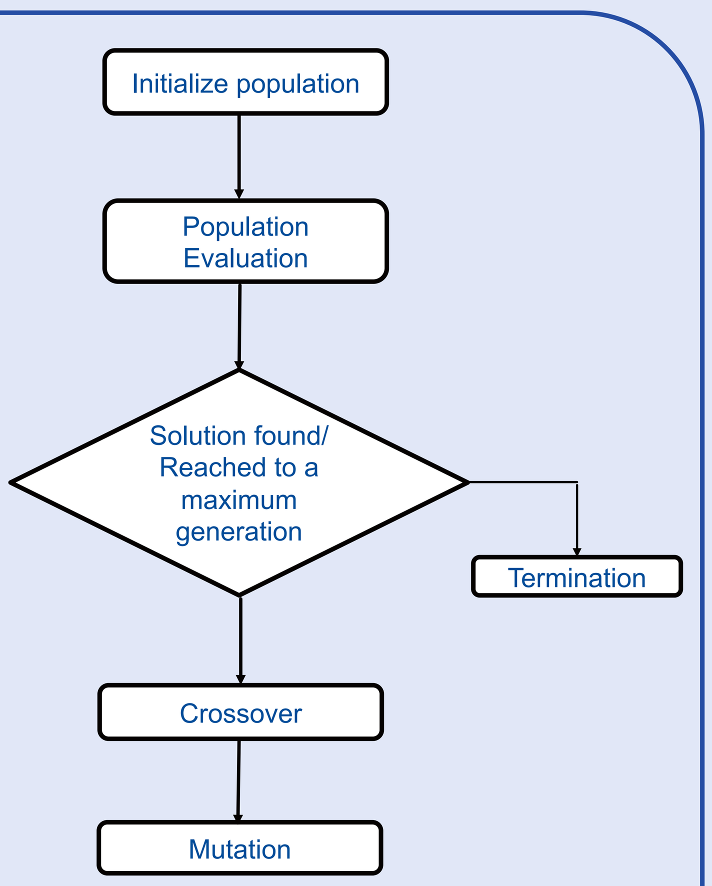
INTRODUCTION

- ER@CEBAF is an extension of the 1-pass energy recovery demonstration in 2003 (CEBAF-ER), with 5-passes.
- A *path length chicane* and *low energy beam dump* are required to set up the energy recovery capability.



EVOLUTIONARY ALGORITHMS

- Inspired by biological evolution, evolutionary algorithms are a popular search technique which require no derivative information.
- Have computational complexities due to stochastic search nature of the algorithm.
- Definition of the objectives is the crucial step in problem definitions.



MULTI-OBJECTIVE OPTIMIZATION

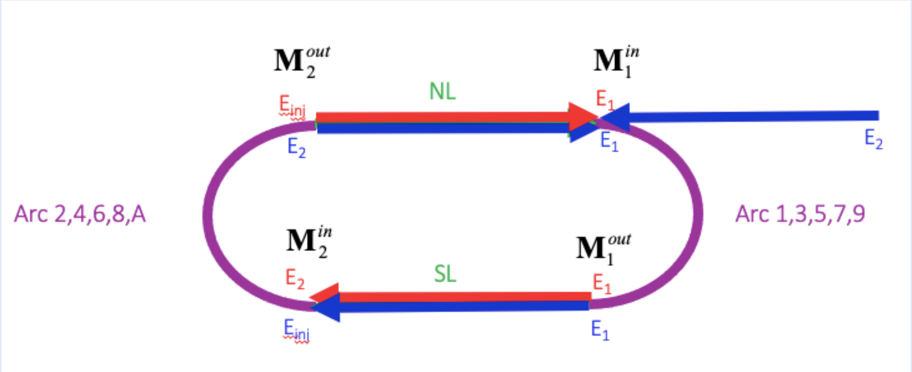
- Multi objective optimization problem definition follows:

$$\begin{aligned} &Minimize_x && F(x) = [F_1(x), F_2(x), \ldots, F_k(x)]^T \\ &subject\ to && g_f(x) \le 0, \quad j = 1,2, \ldots k \\ & && h_l(x) = 0, \quad l = 1,2, \ldots, e \end{aligned}$$

- Outcome is the 'Pareto-optimal set' with non-dominated solutions.
- Ranking algorithm based on non-dominated sorting (NSGA II)[6] using an elitism mechanism.

MULTIPASS LINAC OPTICS

- Multipass linac optics consider the beta evaluation for 5- accelerating and 5- decelerating passes through a linac.
- Illustration of decelerating pass is done by arranging the lattice elements in a reversed order.
- Combining accelerating and decelerating passes without using arcs, is done with zero length (M) matrix.



$$M = \begin{bmatrix} \beta_x \\ -\alpha_x \\ \beta_y \\ -\alpha_y \end{bmatrix}$$

OBJECTIVE DEFINITION:

- Lattice optics optimization suppressing beam-break-up (BBU) instabilities is done by tuning quadrupole focusing.

$$I_{th} = \frac{2pc}{e\omega Q\frac{R}{Q}} \frac{1}{|T_{12}| sin(\omega T_{tr})}$$

$$\left\langle \frac{\beta}{E} \right\rangle = \int \frac{\beta}{E} ds$$

- Beta values of lowest energy pass required to be small and tighter, whereas higher pass optics need to preserve mirror symmetric behavior in accelerating and decelerating passes to rescale isochronous arcs.
- Three objective functions to characterize lattice optics.

$$F_1 = \text{MSE}[\text{moving avg.}(\beta_x), \text{moving avg.}(\beta_y)]$$

$$F_2 = \left(\prod_{i=x,y} \frac{1}{n} \left(\sum_{i=1}^{10} \beta_{i-\max} \right) \right)^{\frac{1}{2}}$$

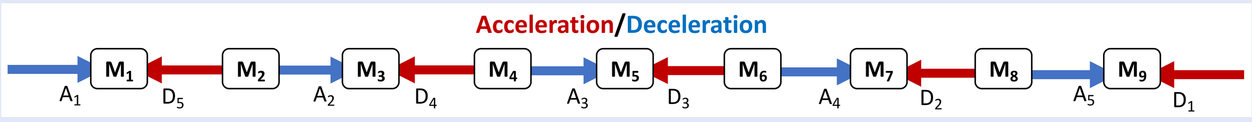
$$F_3 = \left(\prod_{i=x,y} \frac{1}{n} \sum_{i=2}^{5} |\beta_{i-\max} - \beta_{i+1-\max}| \right)^{\frac{1}{2}}$$

- Each function couples both horizontal and vertical beta-variations.
- Lattice optics optimization becomes a multi-objective optimization as this involve minimization of F_1 , F_2 and F_3.
- Two constraints defined to control lower pass peak values.

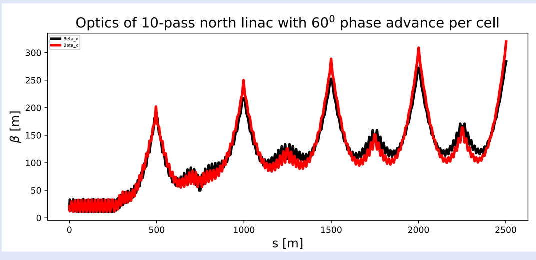
$$C_1 = \beta_{x-\max}^{1^{st}\text{pass}} - 60\ m \qquad C_2 = \beta_{y-\max}^{1^{st}\text{pass}} - 60\ m$$

RESULTS AND DISCUSSION

- 10 pass beamline was created for CEBAF North Linac.

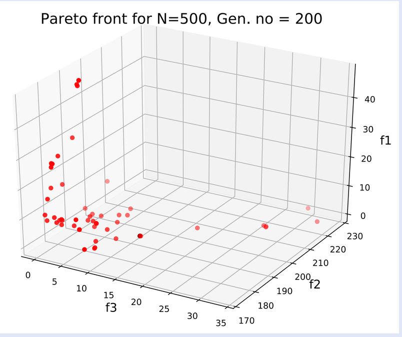


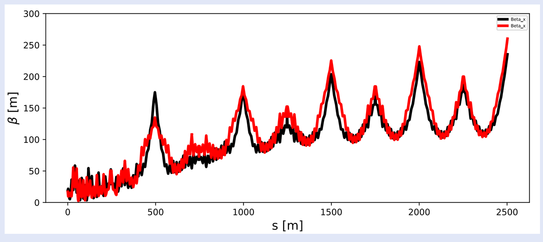
- Manually optimized optics for this beamline correspond to 60^0 phase advance FODO like linac.



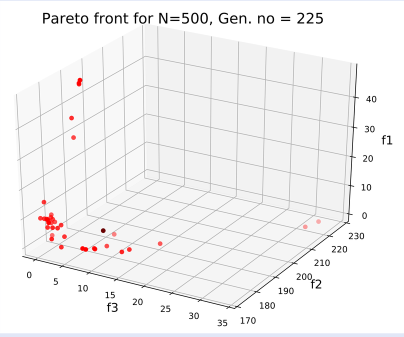
- 26 quadrupoles + initial Twiss values in the 10 pass NL beamline are tuned to obtain best optics required for multipass Energy Recovery. → **30-D Search Problem**
- For N=500, results of two different searches.

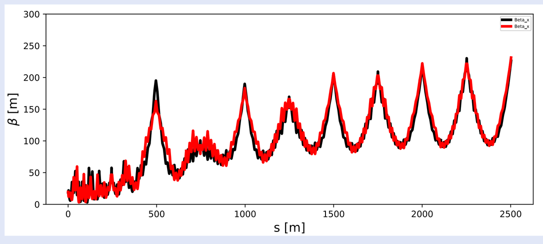
Gen. no = 200





Gen. no = 225





- One 'best' lattice setting from each search result were chosen and optics are displayed.
- Pareto optimal set converges as the generation number increases, while mirror-symmetry $\boldsymbol{\beta}$ variations in higher passes have improved with larger generation number.
- Selection of an optimal solution compromise either the tighter control of the 1st pass or the mirror-symmetry or higher passes.
- Required humongous computational time limits the use of higher population size & generation numbers.
- Studies on reducing the search space is carried out with the quadrupole field variations on the Pareto optimal set.

* **Pymoo** python framework is used to implement NSGA II optimization and **ELEGANT** particle tracking code is used to get lattice optics.

FUTURE WORK

- Optimized lattice setting for 10 pass NL can be used to design the 10 pass South Linac beamline.
- Rescaling the arcs is possible using the Twiss values at the linac boundaries for each pass, then the 10-pass ER@CEBAF lattice will be obtained.

CONCLUSIONS

- Population size needs to increase with increase of search space. Decrease of the search space is possible with the magnetic field variation analysis.
- Optics of the resulted lattice settings from EA-MOO search are in good agreement with the expected multipass ERL requirements.

ACKNOWLEDGEMENT

- This material is based upon work supported by the U.S. Department of Energy under contract DE-AC05-06OR23177.

#ineth001@odu.edu

REFERENCES

[1] S. A. Bogacz et. al., "ER@CEBAF:A test of 5-pass energy recovery at CEBAF", (BNL--112411-2016-IR), 2016.
[2] A. Bogacz, "Challenges and Opportunities of Energy Recovering Linacs", LAL Seminar, Orsay, 2017.
[3] A. Bogacz, A. Latina, D. Pellegrini, "LHeC ERL Design and Beam-dynamic Issues", ERL-2015.
[4] R. Marler, J. Arora," Structural and Multidisciplinary Optimization", vol 26, 2004.
[5] D. Pellegrini, "Beam Dynamics Studies in Recirculating Machines", Doctorial Thesis.
[6] K. Deb, "A Fast and Elitist Multi-objective Genetic Algorithm: NSGA-II", IEEE Transactions on Evolutionary Computation, Vol6, 2002
[7] J. Blank, K. Deb, "Pymoo: Multi-Objective Optimization in Python", 2020
[8] I. Neththikumara et. al. "An Evolutionary Algorithm Approach to Multi-pass ERL Optics Design", IPAC 2021, Brazil.