# LINAC OPTICS OPTIMIZATION WITH MULTI-OBJECTIVE OPTIMIZATION *

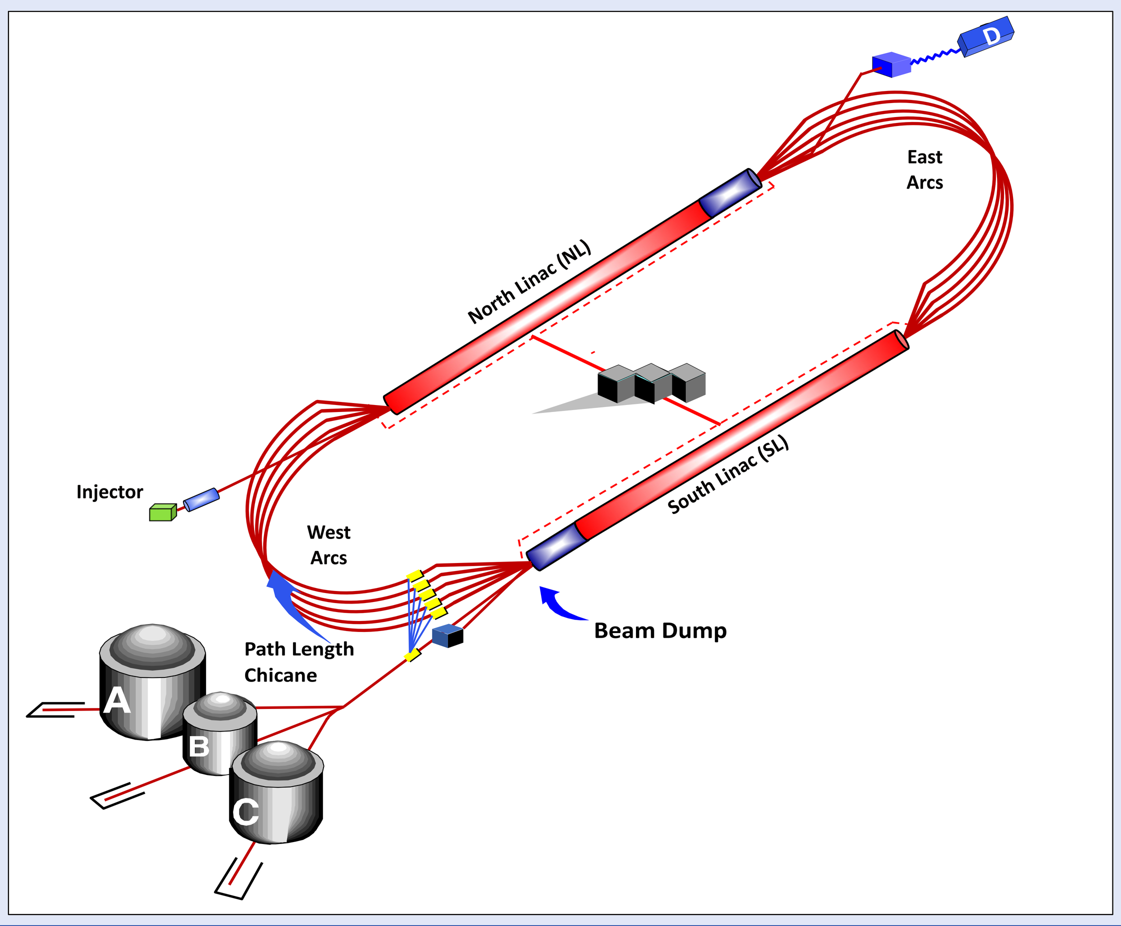
I. Neththikumara[1 #], T. Satogata[1,2], S.A. Bogacz[2], R.M. Bodenstein[2], A. Vandenhoeke[3]
[1] Center For Accelerator Studies, Old Dominion University, Norfolk, VA 23529, U.S.A.
[2] Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, U.S.A.
[3]Artificial Intelligence Lab, 1050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

## ABSTRACT

The beamline design of recirculating linacs requires special attention to avoid beam instabilities due to RF - wakefields. A proposed high-energy, multipass energy recovery demonstration at CEBAF uses a low beam current. Stronger focusing at lower energies is necessary to avoid beam breakup (BBU) instabilities, even with this small beam current. The CEBAF linac optics optimization is focused on balancing over-focusing at higher energies and beta excursions at lower energies. Using proper mathematical expressions, linac optics optimization can be achieved with evolutionary algorithms. Here, we present the optimization process of North Linac optics using Multi-Objective Optimization.

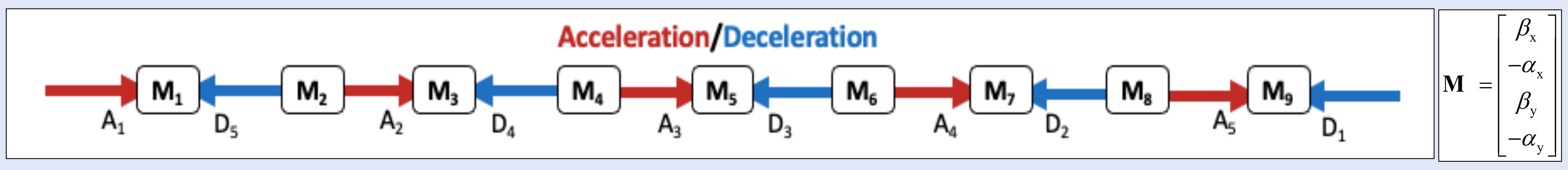
## INTRODUCTION

ER@CEBAF is a multipass, multi-GeV energy recovery demonstration proposed at CEBAF accelerator. This is an extension of the 1-pass energy recovery demonstration in 2003 (CEBAF-ER), with 5-passes.

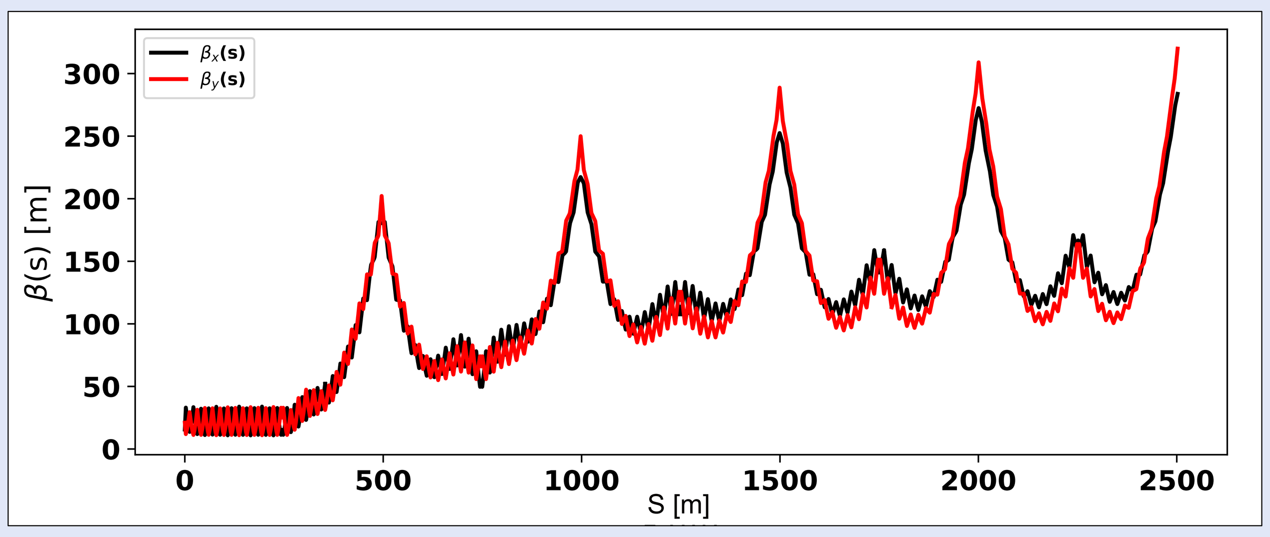



## MULTIPASS LINAC OPTICS

Multipass linac optics consider the beta evaluation for 5-accelerating and 5-decelerating passes through a linac. Illustration of a 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 matrix (M), matching arc end optic conditions.




Manually optimized optics for this 10-pass NL beamline correspond to $60^0$ phase advance FODO like linac.




## MULTI-OBJECTIVE PROBLEM DEFINITION

**Objective Definition:**

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

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

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

Beta values of the lowest energy pass required to be small and tighter, whereas higher pass optics need to preserve mirror symmetric behavior in accelerating and decelerating passes in order to rescale isochronous arcs.
Optimization problem requires multiple objectives.

- Three objective functions used to characterize 10-pass linac lattice optics.

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

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

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

- Two constraints defined to control lower pass peak values.

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

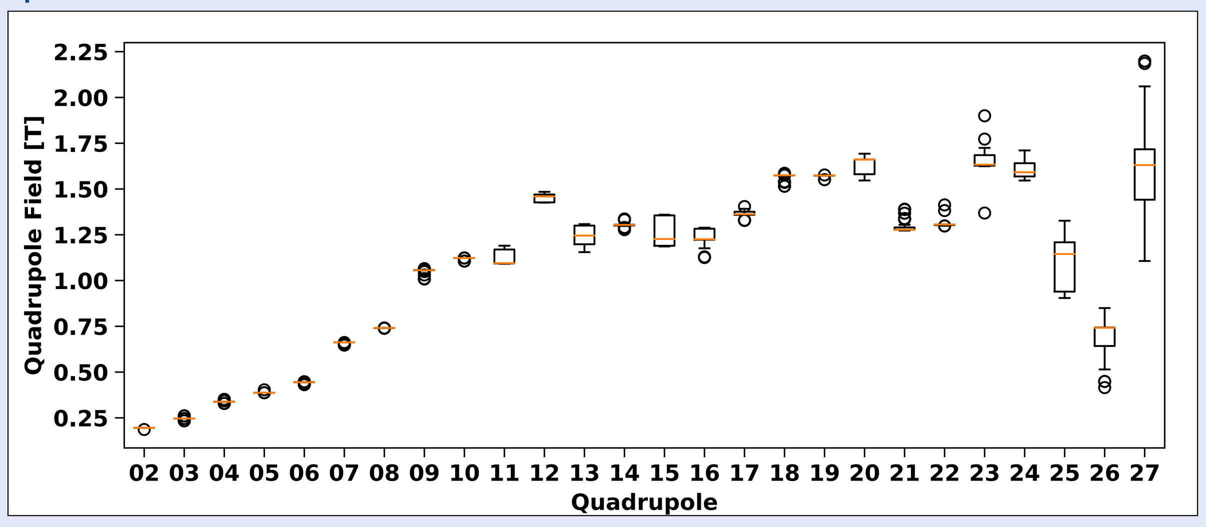
26 quadrupoles + initial Twiss values (4) in the 10- pass beamline are tuned.

30-D Search Problem → Large population size → Large computational time

## RESULTS AND DISCUSSION

**Magnetic Field Variation Analysis:**

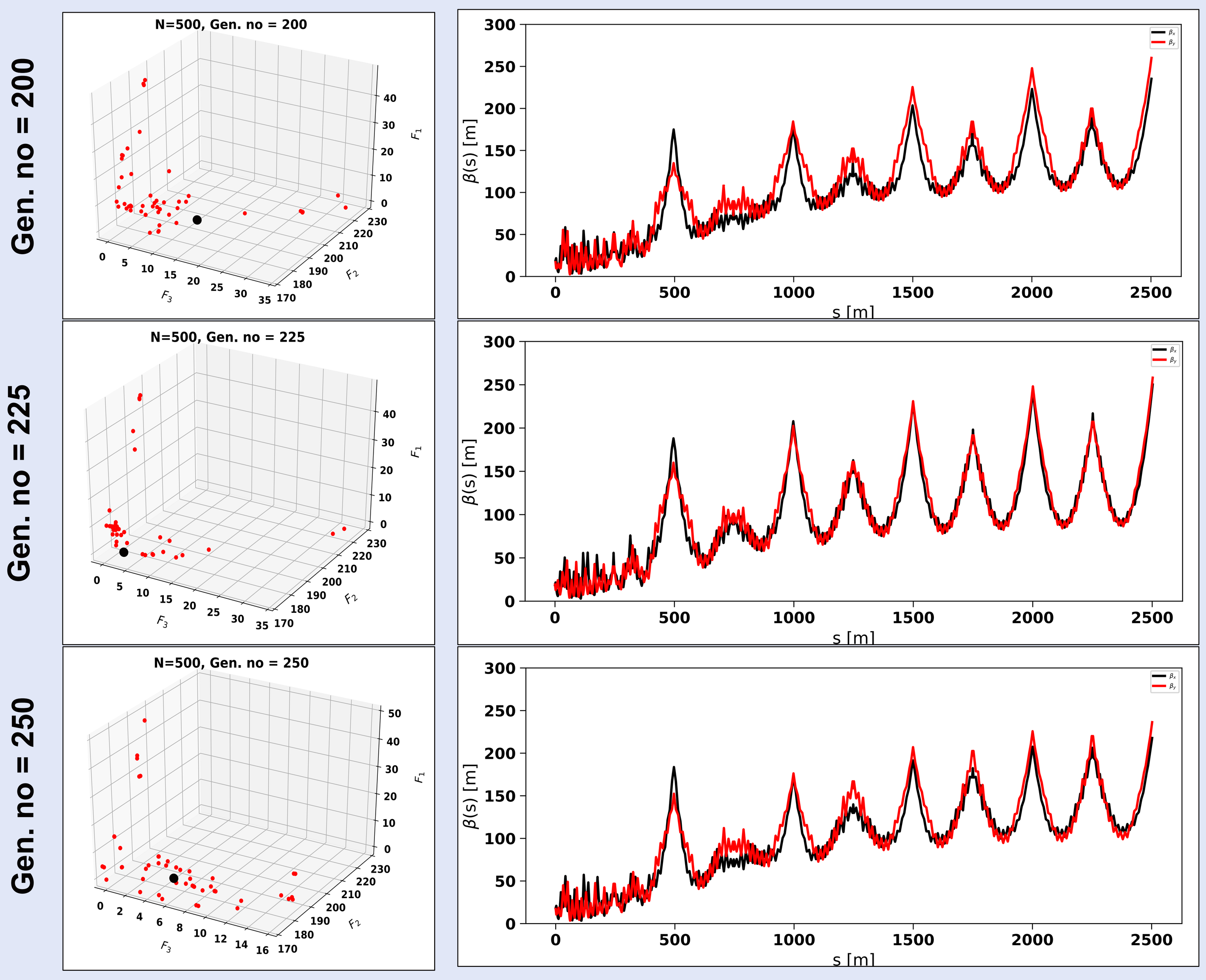
Field variation of 26 quadrupoles of Pareto front individuals were analyzed, to simplify search space.




Reduction of search space → Reduction of computational time

Magnetic field variations in box plots for Pareto front individuals for N=500, gen. no=200

**30-variable search results:**




Pareto fronts for three different searches for 30-variables and optics of a best solution from each search

- Pareto optimal set converges as the generation number increases, while mirror symmetry $\beta$-variations in higher passes have improved with larger generation number.
- Selection of an optimal solution compromise either the tighter control of the $1^{st}$ pass or the mirror symmetry or higher passes.
- Required humongous computational time limits the use of higher population size & generation numbers.

## CONCLUSIONS

- Adequate population size and generations are required with larger search space.
- Decrease of the search space is possible with the magnetic field variation analysis.
- Limiting the search space, reduces required population size, hence computational time.
- Optics of the resulted lattice settings from EA-MOO search are in good agreement with the expected multipass ERL requirements.

## FUTURE WORK

Optimized lattice setting for 10-pass NL can be used to design the 10-pass South Linac beamline. Rescaling the arcs to match linac optics will be done in OptiM, creating the 10-pass ER@CEBAF lattice.

## ACKNOWLEDGEMENT

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#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] J.J Bisognano and J. Krafft. "Multipass beam breakup th3-9 in the cebaf superconducting linac", 1986
[3] S. A. Bogacz, "Challenges and Opportunities of Energy Recovering Linacs", LAL Seminar, Orsay, 2017.
[4] S. A. Bogacz, A. Latina, D. Pellegrini, "LHeC ERL Design and Beam-dynamic Issues", ERL-2015.
[5] S.A. Bogacz et al. "CEBAF Energy Recovery Experiment". In: *Proc. PAC 2003* IEEE supplement (2003), pp. 195–198.
[6] R. Marler, J. Arora," Structural and Multidisciplinary Optimization", vol 26, 2004.
[7] K. Deb, "A Fast and Elitist Multi-objective Genetic Algorithm: NSGA-II", IEEE Transactions on Evolutionary Computation, Vol6, 2002
[8] J. Blank, K. Deb, "Pymoo: Multi-Objective Optimization in Python", 2020.
[9] I. Neththikumara et. al. "An Evolutionary Algorithm Approach to Multi-pass ERL Optics Design", IPAC 2021, Brazil.