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ICABU 2023

The 25th International Conference on Accelerators and Beam Utilization

November 8 (Wed) – 10 (Fri), 2023

IBS Science Culture Center, Daejeon, Korea

KOREA University
Sejong campus

ICABU 2023

Design and Optimization Study of the Electron Linear Accelerator for the Korea 4th-generation synchrotron radiation Using Multi-Objective Genetic Algorithm

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Outline

1. Introduction to Electron Linear Accelerator for Korea-4GSR

2. Multi-Objective Genetic Algorithm(MOGA)

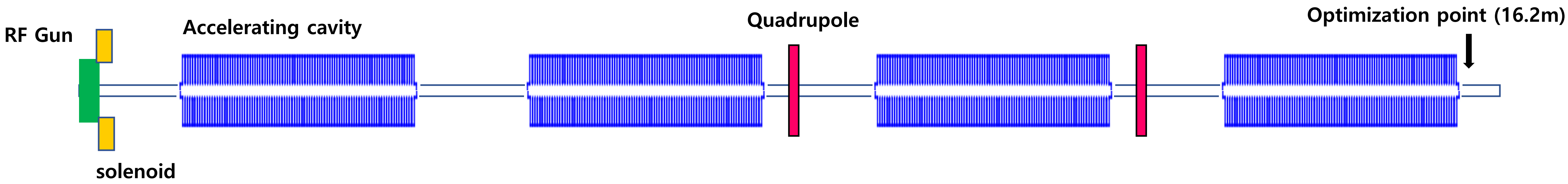
3. Optimization Study of the Electron Linac

4. Error Study of the Electron Linac

5. Summary

Electron Linear Accelerator for Korea-4GSR

layout



Beam parameters

	Single-bunch mode	Multi-bunch mode
Energy	200 MeV	200 MeV
Frequency	2997.56 ± 0.1 MHz	2997.56 ± 0.1 MHz
Emittance (at 200 MeV)	≦ 10 nm	≦ 10 nm
Relative energy spread (rms)	≦ 0.5 %	≦ 0.5 %
Pulse to Pulse energy jitter(rms)	≦ 0.2 %	≦ 0.2 %
Bunch charge (charge stability)	0.01 to 1 nC (2%)	1 to 3 nC (5%)
Pulse duration	6-8 ps FWHM	≈200 ns
Repetition rate	2 Hz (60 Hz)	2 Hz

The electron linac design goal
: minimization energy spread and transverse emittances

The requirement beam parameters
: beam energy, bunch length, beam size …

Beam tracking code
: ASTRA code
Optimization algorithm
: Multi-Objective Genetic Algorithm (MOGA)
Tool
: pymoo (base : python)

To three objectives minimized simultaneously, satisfying many constraints by beam line parameter, The MOGA are used for optimization.

Multi-Objective Genetic Algorithm (MOGA)

Optimization problem

$$
\begin{array}{llll}
\min & f_m(x) & m = 1,..,M & \text{: objective} \\
\text{s.t.} & g_j(x) \leq 0 & j = 1,..,J & \text{: constraint} \\
 & h_k(x) = 0 & k = 1,..,K & \\
 & x_i^L \leq x_i \leq x_i^U & i = 1,..,N & \text{: variable}
\end{array}
$$

The objective functions
: The goal is to optimize the quantities users want in start to end simulations.

The constraint functions
: Constraints on calculated quantities

The variables
: upper and lower values allowed in our "knobs"

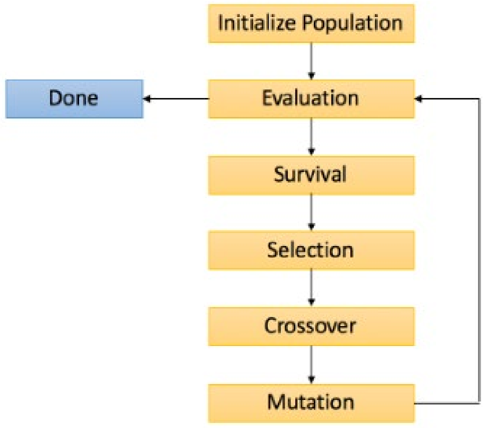
This method is to maximize or minimize the objective function while satisfy equality constraint function.

Multi-objective optimization

- Optimization problems with more than one **objective functions** to be satisfied
- The objective functions may be **conflicting** with another
- In order to simplify the solution process, additional objective functions are usually handled as **constraints**
- **Multiple objective functions** are handled at the same time

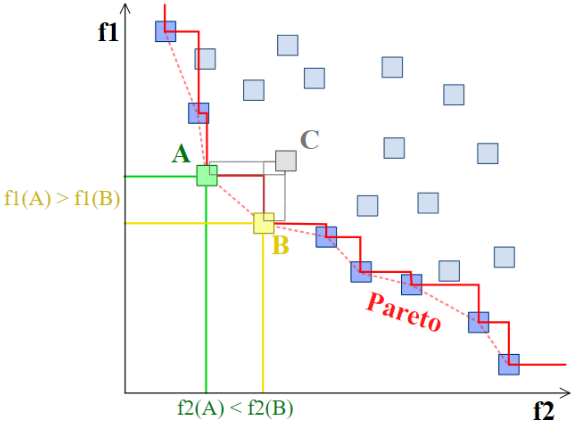
Multi-Objective Genetic Algorithm (MOGA)

Genetic algorithm



- **Initial population** of trial parameters are set.
- Solution for the first generation are **evaluated**
- By examining these solutions, **survival** and **selection** steps are processed
- In **crossover** and **mutation** steps, offspring are generated using survived data from the previous generation.
- Survivals and offspring form the next generation.
- the evaluation step for the new generation processes.

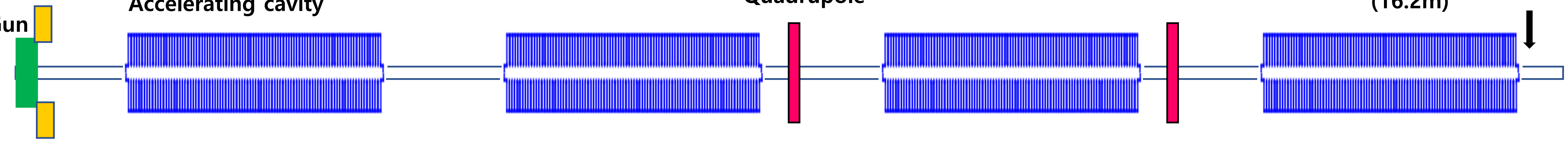
The pareto front



- **The pareto front** is propagated to the left-bottom corner in objective space.
- All pareto-optimal solutions are **non-dominated**
- The line is the **pareto-optimal front** and the solutions on it are called pareto-optimal
- To get better solutions, the pareto front analyzed to process the data
- The goal of multi-objective optimization is to find the pareto front, as generation evolves

Optimization Study of the Electron Linac

The problem functions and variables



Objectives (3)		Unit
Normalized rms emittance X&Y	Minimization	mm-mrad
rms energy spread	Minimization	keV

Constraint (7)		Unit
Beam size X &Y (rms)	< 0.3	mm
Divergence X&Y	< 0.2663	mrad
Bunch length	< 1.0	mm
Transmission rate	>99.99	%
Average energy	>200	MeV

Variables (6)	range	unit	
RF gun phase	-20~20	degree	Auto phase
Acc1&2 phase	-20~20	degree	
Acc3&4 phase	-20~20	degree	
Solenoid	0.15~0.21	T	
Quad 1&2	1~3(-4~-1)	T/m	

- **Objective functions**

 - Minimize rms energy spread and emittance to design considering both transverse and longitudinal beam conditions.

- **Constraint functions**

- Limit beam size, angle, bunch length, beam energy, and transmission rate

- **Variables**

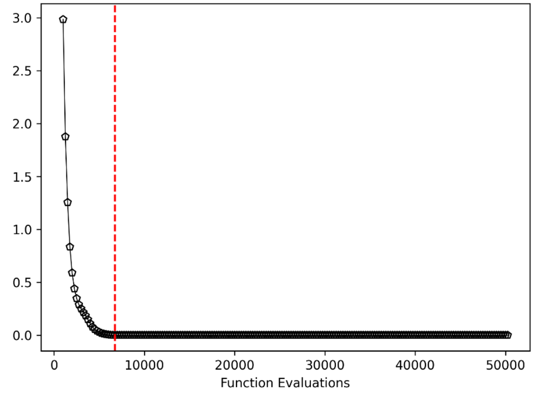
- input phase of the RF cavities and strength of solenoid and quadrupole magnets

- The position of each device is fixed and pre-determined based on frequency

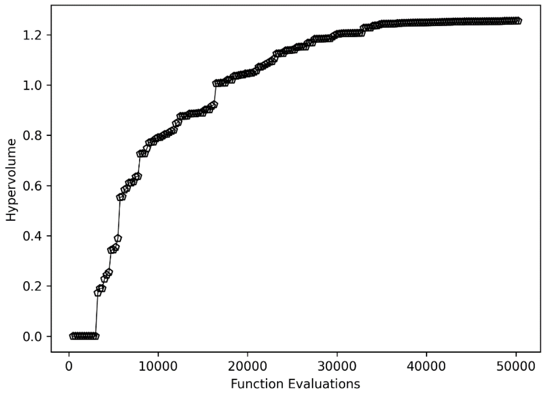
Optimization Study of the Electron Linac

Verification of optimization

constraint violation



hypervolume

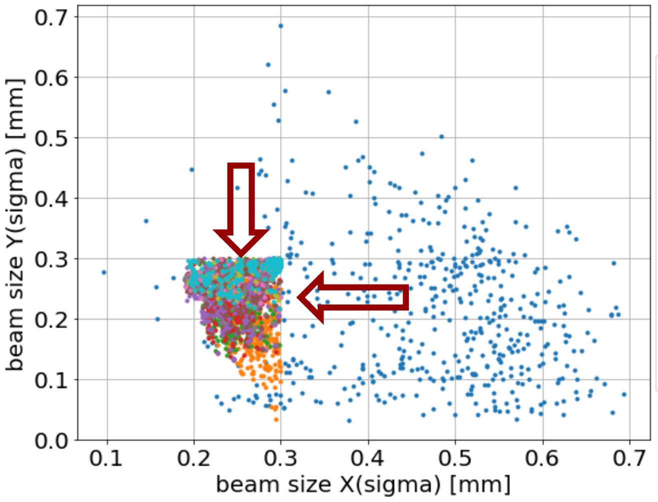


Constraint Violation and Hypervolume :. Constraint violation measures how well the solutions adhere to constraints, while hypervolume provides an indicator of optimization quality.

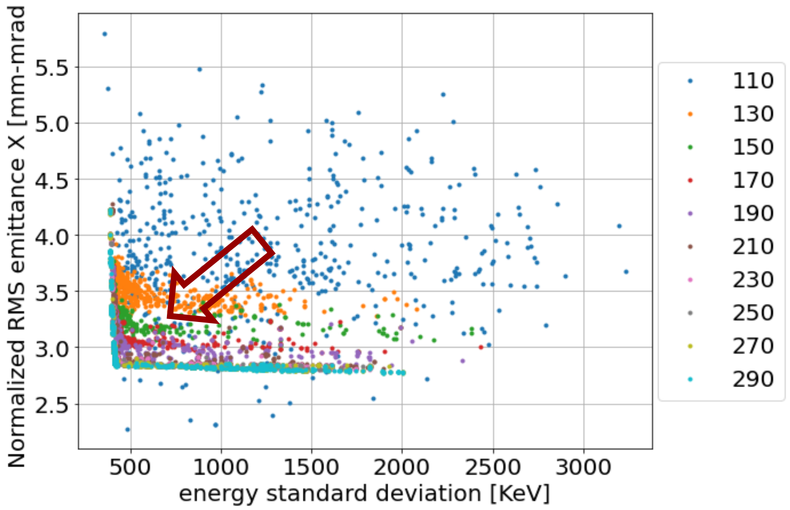
The hyper-parameters in MOGA**(population, offspring and generation)** are determined by fast saturation in constraint violation and hypervolume.

Population : 500 / offspring : 250/ generation : 300

Constraints space



Objectives space



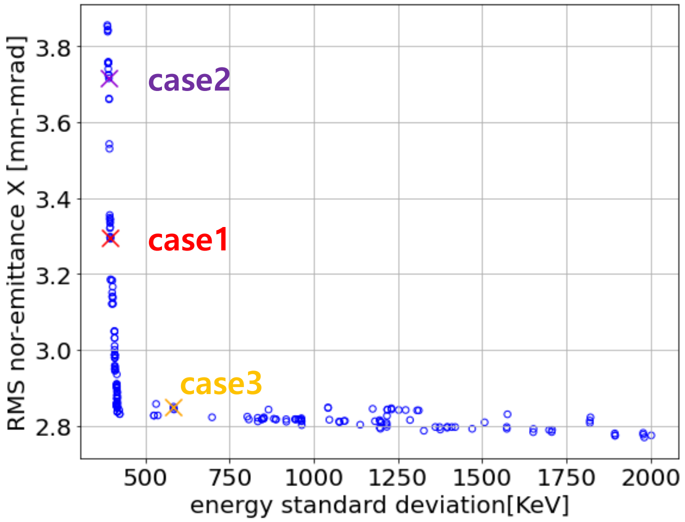
Constraint Space: As generations progress, the algorithm aims to reach values that satisfy the given constraints.

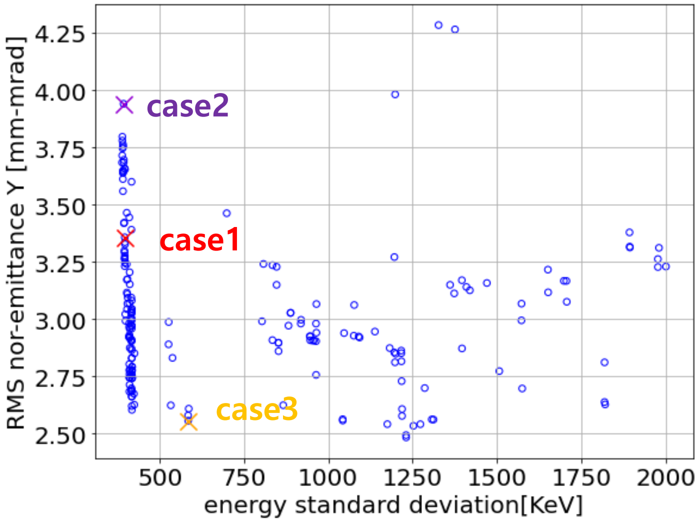
Objective Space: The goal is to minimize values as generation evolve.

Optimization Study of the Electron Linac

Optimization result (generation : 300)

Objectives space





Objective weights

	longitudinal	Transverse	
	Energy spread	Emittance X	Emittance Y
Case1	0.5	0.25	0.25
Case2	0.8	0.1	0.1
case3	0.3	0.35	0.35

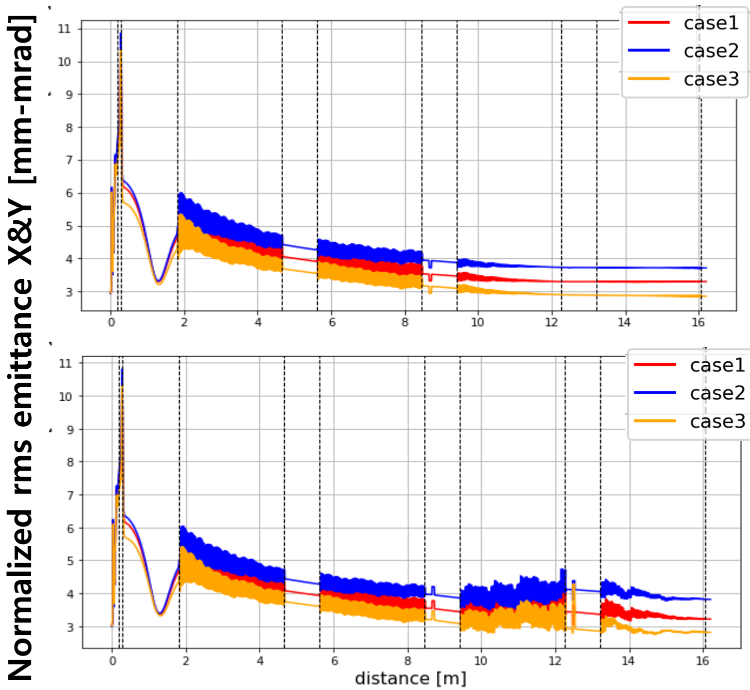
The non-dominated solution form **Pareto front** in objective space

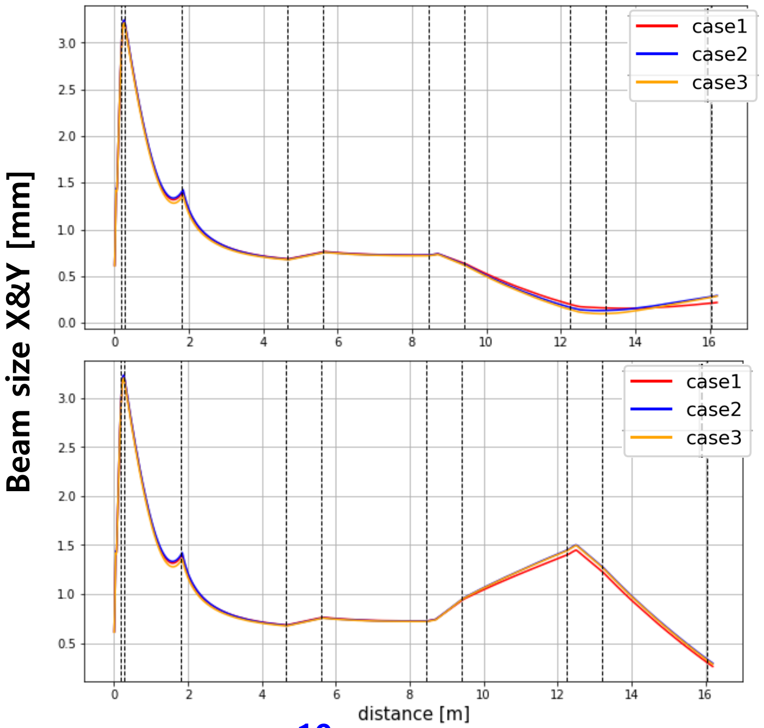
The three cases selected to compare beam tracking simulation based on the importance of objectives

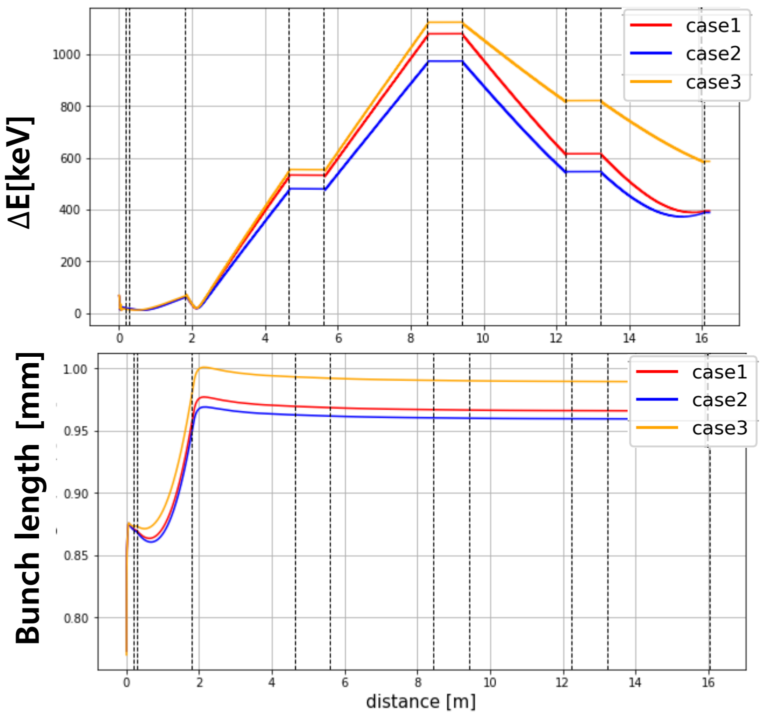
The varying weights on each objective : energy spread, horizontal emittance, vertical emittance

Optimization Study of the Electron Linac

The result of beam tracking simulation







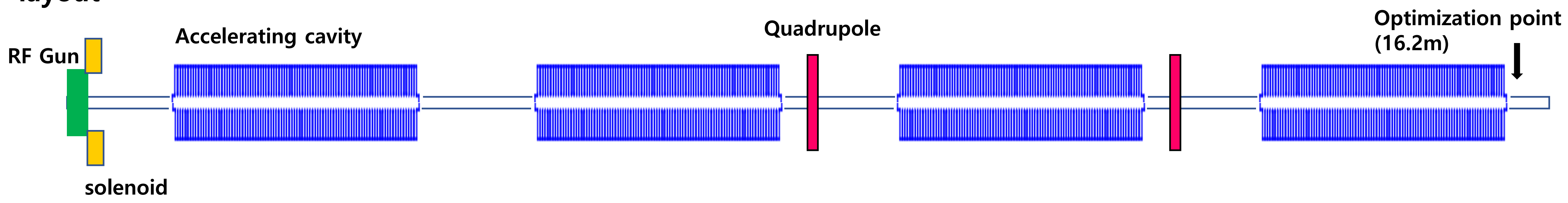
<1MeV(0.5%) <10nm <10nm < 1mm

mode	Energy spread [keV]	emittanceX [mm-mrad]	geometric emittance X [nm]	emittanceY [mm-mrad]	geometric emittance Y [nm]	Xrms [mm]	Yrms [mm]	L_bunch [mm]	Transmission rate [%]	average E [MeV]
Case1	381.50	3.2990	8.44	3.2145	8.18	0.21760	0.26149	0.96584	100	200.16
Case2	372.17	3.7122	9.52	3.8144	9.71	0.29162	0.29447	0.95932	100	200.61
Case3	584.24	2.8520	7.37	2.8147	7.21	0.28593	0.28566	0.98924	100	200.92

In ideal design, all cases meet the requirement. these case are tested their reliability in operation from error study.

Error Study of the Electron Linac

layout



Error parameters

parameters		sigma	
RF gun	gradient	0.2	%
	input phase	0.2	degree
accelerating cavity	gradient	0.2	%
	input phase	0.2	degree
solenoid	strength	0.1	%
quadrupole	strength	0.1	%

Error cutoff : 2 sigma (gaussian)
Random number : 1000

⇨

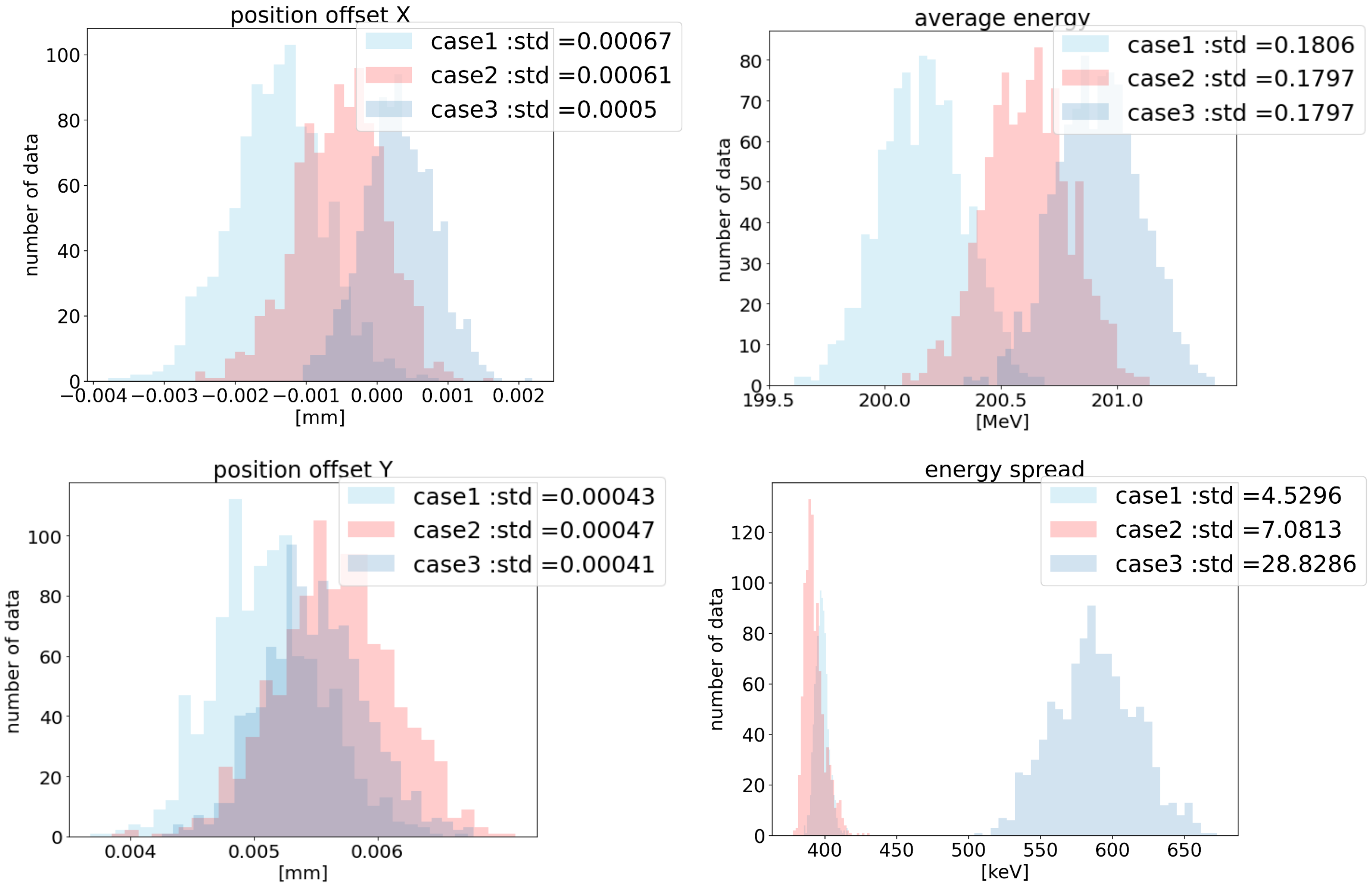
target		
Energy spread	0.5	%
Average energy	0.2	%
Position x,y	10	%

The purpose of error study

- Comparative error study of electron linac based on different objective weights.
- To verify whether the electron linac optimized using MOGA can still meet the target parameters in the presence of errors and to confirm its practical applicability through error study.

Error Study of the Electron Linac

The result histogram of error study



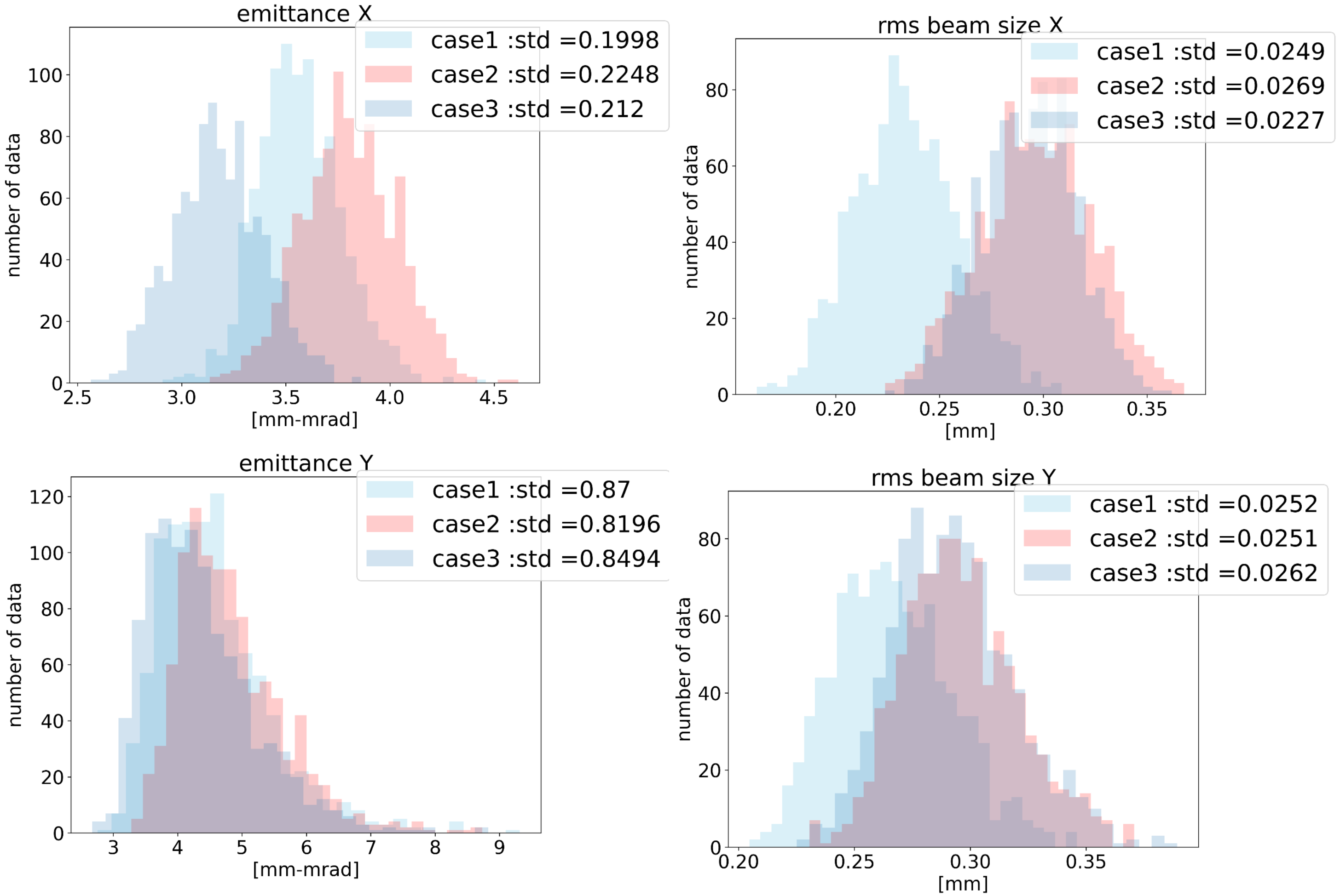
target		
Position offset	0.03	mm
Average energy	0.4	MeV
Energy spread	5	keV

- All case meet the target for position offset and average energy
- The energy spread target is only satisfied in case 1

Case1, which meets all three targe, has been selected as the optimal electron linac design set

Error Study of the Electron Linac

The result histogram of error study



Standard deviation

mode	Energy spread [keV]	emittanceX [mm-mrad]	emittanceY [mm-mrad]	Xrms [mm]	Yrms [mm]
Case1	4.5296	0.1998	0.87	0.0249	0.0252
Case2	7.0813	0.2248	0.8196	0.0269	0.0251
Case3	28.8286	0.212	0.8494	0.0227	0.0262

mode	Offset X [mm]	Offset Y [mm]	L_bunch [mm]	average E [MeV]
Case1	0.00067	0.00043	0.0043	0.1806
Case2	0.00061	0.00047	0.0043	0.1797
Case3	0.0005	0.00041	0.0044	0.1797

The operation values optimized using MOGA are suitable for operation

Summary

Electron lianc design

- Designed of 200 MeV electron linac, injection system for Korea-4GSR
- Using MOGA for optimization and beam tracking simulation with ASTRA code

Optimization study of the Electron Linac

- Objective functions : energy spread and transverse emittance
  Constraint functions : beam size, average energy, transmission rate …
- Optimized electron linac was obtained from 300 generations, and three cases were selected for error study verification.
- Energy spread was within 0.5% and unnormalized rms emittance was below 10nm.

Error study of electron linac

- Error parameters : cavity and magnet (error values : one sigma , cutoff two sigma, gaussian distribution)
- In the result histogram, the beam parameters variations are minimal.
- The optimized results using MOGA are expected to be usable for experiment.

In this study, we design an electron linac that meets the requirements using MOGA. The beam line parameters are suitable for operation.

Thank You for Your Attention