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BEAM DYNAMICS OPTIMIZATION OF AN ELECTRON LINAC USING THE MULTI-OBJECTIVE GENETIC ALGORITHM

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Abstract

A beam dynamics optimization study of an electron injector linear accelerator including an RF photoinjector gun was performed using Multi-Objective Genetic Algorithm for Korea 4th generation storage ring. To meet the requirements of electron beam characteristics at the linac end, the optimization goal was to minimize transverse beam emittance and energy spread. The transverse and longitudinal beam sizes were constrained to find Pareto fronts effectively. Parameters to be optimized were the input phases of the RF gun cavity and accelerator column cavity as well as the strength and position of the focusing solenoids. In addition to finding physical optimization parameters, we also investigated hyper-parameters in optimization simulations such as population, offsprings, generations, etc. This paper presents the optimization results of the linac design.

INTRODUCTION

The development of 4th generation light sources is a significant advancement in scientific research across a range of fields including condensed physics, chemistry, biology, materials science, and more. As a result, there is a global trend towards the development of next-generation light sources, such as 4th generation storage ring facilities, which are designed to produce high-brightness photon beams [1]. This technology provides researchers with the ability to study the properties and behavior of materials and biological systems at the atomic and molecular level, which can lead to important insights and potential applications. As part of this trend, a new construction plan has been initiated in South Korea for a 4th generation storage ring facility. This facility is expected to offer researchers enhanced capabilities for studying a wide range of scientific questions and practical applications [2, 3].

We have designed an injector system for the Korea 4th Generation Storage Ring (Korea 4GSR), which is composed of an electron linac, a booster ring, and a storage ring. The beam is first accelerated to 200 MeV in the injector linac and then further boosted to 4 GeV through the booster ring before being injected into the storage ring to generate synchrotron radiation. The Korea 4GSR is specifically designed to achieve high brilliance, high flux, and small wavelengths from high current and low emittance beam. Therefore, we prioritized the minimization of transverse emittance and energy spread in our linac design. Our focus on these key parameters is intended to ensure optimal performance and to enhance the scientific outcomes of the facility. Through careful consideration of various design parameters and the utilization of advanced optimization techniques, we have developed an injector system that is designed to meet the specific requirements of the Korea 4GSR. To optimize the performance of the linac, we utilized a Multi-Objective Genetic Algorithm (MOGA) [4] to optimize the cavity geometries and linac parameters. The cavity parameters were calculated using the Superfish code [5], and the optimization objectives for cavity geometry were to maximize R/Q and minimize stored energy. For optimization of the beam dynamics simulation, we utilized the Parmela code [6]. To ensure optimal performance, we also took into consideration the booster ring injection condition when designing the linac. Our main goal was to minimize the emittance and energy spread of the beam at the linac end, thus improving the overall efficiency of the beam acceleration.

OPTIMIZATION OF THE CAVITIES GEOMETRY

We have designed two types of RF cavities for our system: the RF gun cavity and the traveling wave accelerating cavity. To determine the optimal geometry of these cavities, we considered five key variables: cavity length (d), inner diameter (b), edge rounding (r2), disk radius (r1), and aperture radius (a), as shown in Fig. 1.

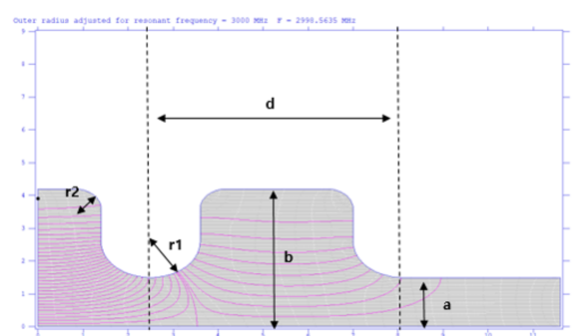

Figure 1: The geometry of RF cavity.

The values of these variables were chosen based on the specific requirements of the design. The two cavities operate in different modes and have different design betas due to their distinct stages in beam acceleration. The RF gun cavity and the first two accelerating cavities are powered by the same

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klystron and therefore operate at the same RF frequency of 3 GHz. The inner diameter of the RF gun aperture was selected to ensure that the laser beam could reach the cathode without obstructing the electron beam propagation. The accelerating cavity's inner diameter was determined based on the desired gradient [7]. This design choice was made based on the specific requirements of each cavity and their respective roles in the acceleration process.

We used a Multi-Objective Genetic Algorithm (MOGA) to optimize the cavity parameters of the RF gun cavity and accelerating cavity. The goal of optimization was to achieve high gradient with low input power, while maximizing R/Q and minimizing stored energy. We used proper hyper-parameters for MOGA simulations to optimize the geometries of both cavities. The final Pareto front data generated by MOGA optimization simulations for the RF gun cavity and accelerating cavity is shown in Fig. 2. From the optimized data, we selected one model for each cavity that met the most important objectives for use in beam dynamics simulation.

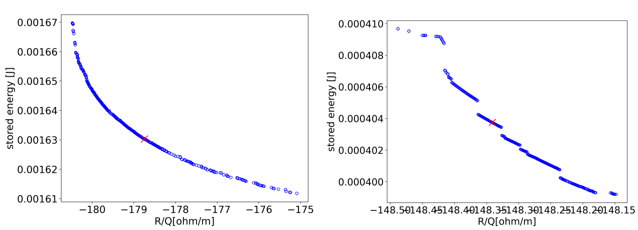

Figure 2: The Pareto Front data of the in last generation of RF gun and accelerating cavity.

The layout of the linac, consisting of an RF cathode gun, four accelerating cavities, and a solenoid, is shown in Fig. 3. The initial beam parameters used in the beam dynamics simulation are listed in Table 1.

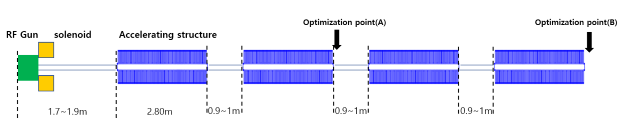

Figure 3: The layout of linac.

Table 1: Initial Beam Parameters

Beam Parameter	Value
Charge	0.01~1 nC
Repetition rate	2 Hz
Laser pulse length	6 ps
Beam size	2 mm

OPTIMIZATION OF THE BEAM DYNAMICS SIMULATION

In our design optimization study, we aimed to meet the beam requirements at the linac end through an optimal combination of accelerating systems. Our objectives for optimization were to minimize beam emittance and energy spread, while meeting the beam size, bunch length, and average energy constraints required for the booster ring. Additionally, we limited the transverse divergence angle to prevent beam spread in the drift space after linac. The objectives and constraints for optimization are listed in Table 2, while the variables for optimization, including positions and input phases of cavities and the strength of the solenoid magnet, are shown in Table 3.

The optimization process for the linac was divided into two steps: the first one focused on the section from the RF gun cathode to the 2nd accelerating cavity exit in optimization point (A), while the second one covered the section from the 2nd to the 4th accelerating cavity in (optimization point (B), as illustrated in Fig. 3. In the middle of the linac, we introduced constraints or modified the beam optics to account for the optimized beam characteristics. In this paper, we present, the optimization results of the first step.

Table 2: The Objective and Constraint Functions of Optimization

Objective function	**Optimization range**	**Unit**
RMS transverse emittance	minimize	
Energy spread	minimize	
Constraint function		
Beam size (rms)	0.2	mm
Transverse divergence angle	0.03	degree
Bunch length (rms)	2.0	degree
Transmission rate	99.99	%
Average beam energy	200	MeV

Table 3: The Variable for Optimization of Beam Dynamics

Variable	**Range**	**Unit**
RF input phase	0~360	degree
Solenoid strength	500~4000	A
Drift1 (RF gun and acc1)	1.7~1.9	m
Drift2 (acc1 and acc2)	0.9~1.0	m

To ensure a successful optimization, we carefully selected the hyper-parameters for the MOGA simulations, such as the population size, offspring number, and number of generations. We also leveraged the pymoo optimization library [8], which also allowed us to use parallel processes and accelerate the optimization process. For the crossover, we found that the uniform case outperformed the SBX method in terms of speed and quality of solutions.

At the first optimization point, we optimized the RF input phase and cavity positions, as well as the solenoid strength,

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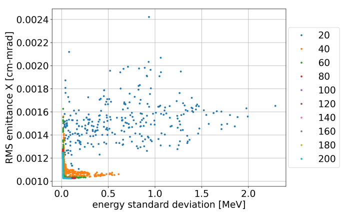
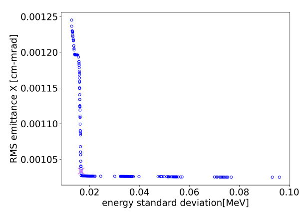
as listed in Table 3. The RF input phase was set to be the same as the one used for the RF gun and accelerating cavity, while the cavity positions were determined based on the reference phase of the beam. The solenoid position was fixed, and only its strength was adjusted during the optimization. During the optimization process from generation 1 to 200, the objectives shifted towards minimization, as depicted in Fig. 4 (a). At generation 200, we generated Pareto front data to evaluate the solutions, as shown in Fig. 4 (b). One of the models with balanced weights for the two objectives was selected and will be used for the second optimization step with the beam dynamics simulation. This model was marked with an X in Fig. 4 (b). At this point, the energy standard deviation was 0.016 67 MeV and the horizontal rms emittance was 0.0103 mm−mrad, meeting the requirements for the linac end.



(a) per generation

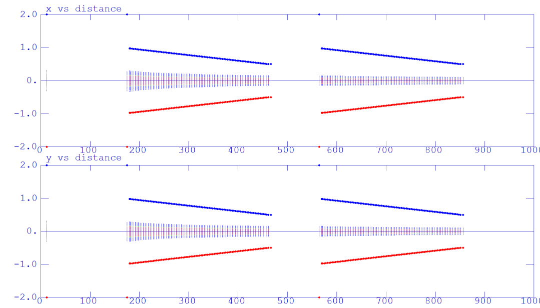


(b) last generation

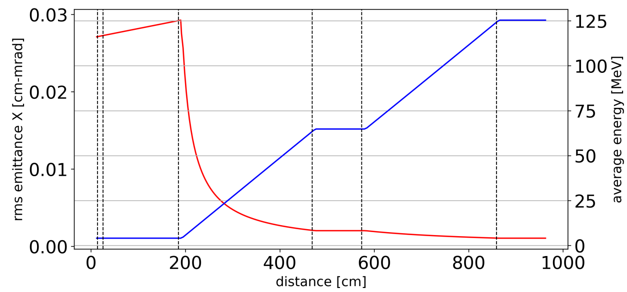
Figure 4: The RMS emittance X and energy spread (a) full data and (b) pareto front data.

To validate the optimized optics obtained at the first optimization point, we performed beam dynamics simulation from the RF gun cathode to the 2nd accelerating cavity. The apertures of the accelerating cavity and beam pipe are shown as the outer red and blue points, respectively, in Fig. 5 (a). The central line in the X or Y axis represents the beam envelope. The transverse beam size and divergence angle were constrained to ensure that the beam is focused on the later beam line. The horizontal rms emittance and average energy are shown in Fig. 5 (b). The positions of one solenoid and two accelerating cavities are indicated by vertical dotted lines.

The simulation results indicate that the average energy requirement of 125.35 MeV can be achieved with a lower input power than used in the simulation. The bunch length is 1.087 degree, and the transmission rate is 99.99%. These results demonstrate the feasibility of the optimized optics obtained at the first optimization point for beam acceleration.



(a) envelope



(b) rms emittance x and average energy

Figure 5: The beam dynamics simulation result (a) envelope (b) rms emittance x and average energy. Vertical dotted lines indicate the entrance and exit positions of solenoid and two accelerating cavities in order from left to right.

CONCLUSION

We conducted a study to optimize the design of the electron linac for the Korea 4th Generation Storage Ring, which will use an injector linac with an RF photocathode gun. To achieve this, we used a multiobjective genetic algorithm to optimize the cavities and beam line optics, with the objective of obtaining a high gradient with low input power while maximizing R/Q and minimizing stored energy. The EM fields of the optimized cavities were used in beam tracking simulations, while the linac optics for solenoid and cavities were optimized in beam dynamics simulations. We took into account several constraints, such as beam size, bunch length, transverse angle, transmission rate, and average energy. The optimization was divided into two steps, with the first step optimizing from the RF gun cathode to the 2nd accelerating cavity and the second step optimizing from the 2nd accelerating cavity to the 4th accelerating cavity. Results of the optimization for the first step show that we achieved an energy spread of 0.016 67 MeV and horizontal rms emittance of 0.0103 mm−mrad as one of the achieved objectives. Our study focused on optimizing up to the middle of the linac, and we plan to continue optimization to the end of the linac in the future.

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