IMPROVING ENERGY SPREAD OF MESA BEAM IN ERL OPERATION*

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Abstract

MESA, the Mainz Energy-Recovery Superconducting Accelerator, currently under commissioning at Johannes Gutenberg University Mainz, is designed to operate in two modes: external beam (EB) mode, with 150 µA polarized electrons at 155 MeV serving the P2 experiment, and energy-recovery linac (ERL) mode, with an unpolarized beam of 1 mA to 10 mA at up to 105 MeV for the Mainz Gas Injection eXperiment (MAGIX) setup. The latter requires precise control of the energy spread and the bunch length across the beam energies of 30, 55, 80, and 105 MeV. Comprehensive simulations were conducted using the tracking code ELEGANT. Starting with a 4-ps bunch length, the full acceleration and deceleration process in ERL mode was modeled by optimizing the RF phase, and the accelerating gradient fields in off-crest operation, resulting in the desired energy gain in each linac section. To reach the lowest energy spread, an appropriately selected longitudinal dispersion in the recirculation arcs is required. Consequently, the injection arc lattice is optimized by adjusting the arc's longitudinal dispersion R_{56} as the primary tuning parameter. The realization of a chirp together with the tuning of R_{56} enhances the overall beam quality.

INTRODUCTION

MESA is a double-sided superconducting recirculating linear electron accelerator designed to operate at different beam energies for nuclear and particle physics experiments [1]. The overall layout of the MESA is shown in Fig. 1. In ERL mode [2], the MAGIX experiment [3] requires a range of beam energies to perform precision electron scattering measurements, including studies related to dark-photon searches and proton-radius measurements. The MAGIX experimental setup relies on high-resolution magnetic spectrometers, where the combined contributions of the spectrometer optics and the beam energy spread determine the achievable energy resolution. To fully exploit the experimental capabilities, the relative beam energy spread at MAGIX must be in the order of 10^{-4} [4]. While ERL operation enables high current, it entails complex longitudinal beam dynamics that can degrade the energy spread at intermediate energies. This work focuses on the analysis and optimization of the longitudinal phase space in the MESA ERL, with particular emphasis on meeting the stringent energy-spread requirements of the MAGIX experiment.

* Work supported by DFG (GRK 2128).
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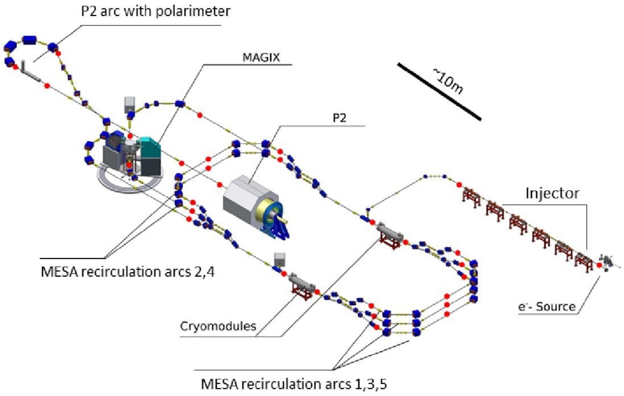

Figure 1: Layout of the MESA facility, starting from the electron source and injector on the right, which provides the low-energy beam guided to the main linac. Downstream of the injector, the beam is accelerated in the first cryomodule located at the central straight section, after which the beam is redirected through arcs 1–5 for acceleration in the first passes and deceleration in the return passes. The MAGIX experiment is located on the upper straight section, while the P2 beamline, with its polarimeter branches off downstream.

LONGITUDINAL PARAMETER OPTIMIZATION

In the ERL operation mode, MESA functions as a multi-turn recirculating linac, in which the electron beam passes twice through the cryomodules, housing two superconducting TESLA-type RF cavities [5], that provide an energy gain of 12.5 MeV per cavity (25 MeV total per pass) before being decelerated to recover the beam energy. Here, the goal is to achieve the correct design energy after each linac pass for proper beam transport, as well as achieving a small energy spread at the MAGIX interaction point. To achieve this, beam-dynamics simulations were performed to identify an optimum working point for the machine. The optimization procedure follows the method successfully used at the Darmstadt multi-turn ERL S-DALINAC [6], adapted here to MESA.

The study focuses on interdependent longitudinal degrees of freedom that manipulate the longitudinal phase space:

The phase-dependent energy gain imparted to each particle as a function of its arrival time is expressed as:

$$\Delta E = qV_{\mathrm{peak},j} \sin(\omega t + \phi_j), \qquad (1)$$

where q is the particle charge, ω is the RF angular frequency, t is the particle arrival time, and $V_{\mathrm{peak},j}$ and ϕ_j are the voltage and RF phase of cavity j, respectively.

The acceleration is performed in a non-isochronous regime, with each cavity operating off-crest ($\phi_j \neq 0$). Particles entering the cavity at different times receive different energy gains, which introduce a correlated energy spread within the bunch. This correlation is essential for maintaining the time–energy structure.

The longitudinal dispersion R_{56} of the arcs manipulates the bunch length by coupling the longitudinal position z to the relative momentum deviation $\Delta p/p_0$. The transport relation can quantitatively describe this effect as,

$$z_f = z_i + R_{56} \cdot \frac{\Delta p}{p_0}, \quad (2)$$

where z_i and z_f are the initial and final longitudinal coordinates, and $\Delta p/p_0$ is the relative momentum deviation.

As a result, $V_{\mathrm{peak},j}$ and ϕ_j per cavity j as well as $R_{56,i}$ per arc section i can be used together with the manipulation of the path length per arc to influence t.

The simultaneous optimization of these parameters defines the full longitudinal phase-space evolution along the MESA beamline, balancing the competing requirements of maintaining the mean energy and energy spread; the goal is to reach a minimal energy spread at the MAGIX target, while at the same time, the energy spread needs to be overall small to ensure loss-free beam transport to the beam dump.

TRACKING SIMULATIONS AND OPTIMIZATION METHODOLOGY

The optimization strategy described above was realized with the software ELEGANT [7] by adapting the simulation code for multi-turn ERLs from Ref. [8]. By this, a start-to-end simulation was evaluated in which the lattice was modeled by using accelerating/decelerating cavities, drift sections, and first-order matrix elements. The simulations were initialized with beam parameters from the MAMBO pre-injector [9]: an initial beam energy of 5 MeV, an rms bunch length of $\sigma_t = 4$ ps, and an rms relative energy spread of $\sigma_\delta = 1.74 \times 10^{-4}$ [4].

The optimization procedure aims to identify a set of longitudinal parameters that satisfy the nominal beam energy after each cavity within a tolerance of 10^{-4} and to minimize the projected energy spread at the MAGIX target. To meet these criteria, the voltages and phases of the four cavities, as well as the path lengths and longitudinal dispersion of the arcs, were adjusted within their operational limits.

OPTIMIZATION RESULTS AND BEAM PERFORMANCE AT THE MAGIX TARGET

In this paper, we will discuss the values of two parameter types only due to space constraints: the cavities' phases and the arcs' longitudinal dispersions (see Tables 1 and 2).

Notably, strong off-crest acceleration/deceleration of the last cavity is required in this solution to compensate for the cumulative phase slippage from different recirculations. For the longitudinal dispersion, only values in the arcs A1 and A3 differ significantly from zero.

Table 1: Off-crest phase shifts of the four RF cavities in the two cryomodules

Phase Shift [°]:	ϕ_1	ϕ_2	ϕ_3	ϕ_4
	9.67	11.99	6.28	17.4

Table 2: Optimized values of the longitudinal dispersion in the injection arc, the three recirculation arcs (A1–A3), and the experimental beamline

R^i_{56} [m]:	R^{inj}_{56}	R^{A1}_{56}	R^{A2}_{56}	R^{A3}_{56}	R^{exp}_{56}
	0	0.28	0.01	0.47	0

Figure 2 shows the simulation results for some beam parameters along MESA. The nominal momentum (and hence energy) is reached after each acceleration stage, confirming proper acceleration and deceleration. At the MAGIX target ($s = 170$ m), the rms relative momentum spread is $\sigma_\delta \approx 8 \times 10^{-5}$ satisfying the experimental requirement, while maintaining a sufficiently small energy spread throughout the entire beamline to remain within the beamline acceptance.

Figure 3 shows the behavior of the longitudinal phase space at characteristic locations along MESA. In particular, the panel at 105 MeV corresponds to the MAGIX target position and exhibits an S-shaped distortion of the distribution. This curvature reflects the influence of the nonlinear terms in the RF field, which become visible after the successive off-crest acceleration and transport through dispersive recirculation arcs. The observed nonlinearity motivates considering second-order longitudinal dispersion (T_{566}) in future studies to achieve an even smaller energy spread at the interaction point.

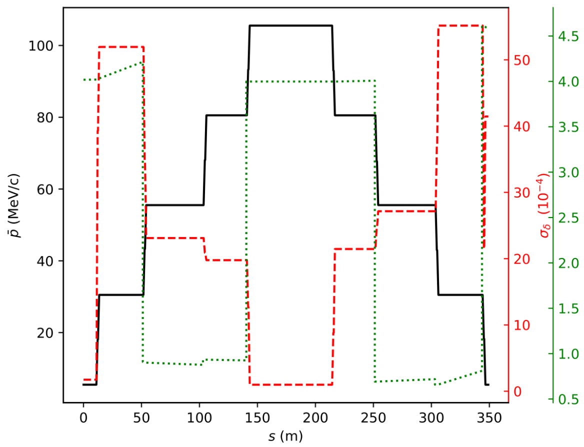

Figure 2: The evolution of beam parameters along MESA as a function of the position s. The black solid line shows the mean momentum, illustrating the successive acceleration and deceleration stages characteristic of ERL operation. The red dashed line depicts the evolution of the rms relative momentum spread σ_δ, while the green dotted line shows the rms bunch length; due to the method used within ELEGANT, the shown rms bunch length is only reliable within the cryomodules.

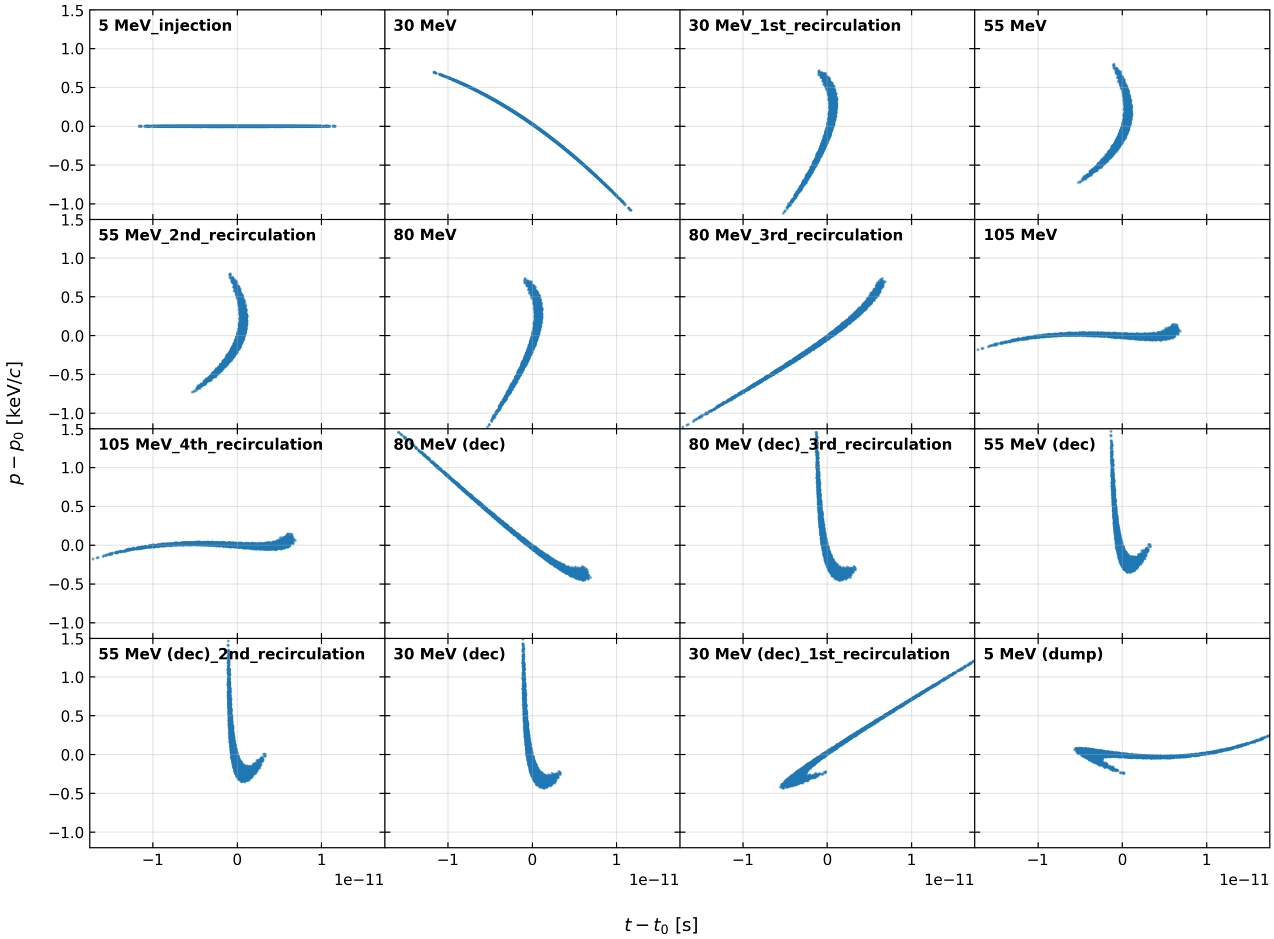

Figure 3: Longitudinal phase-space evolution: each panel shows $p - p_0$ versus $t - t_0$ at successive stages of MESA. The sequence follows the beam from injection at 5 MeV through the accelerating passes at 30, 55, 80, and 105 MeV (including the recirculation arcs), and subsequently through the full deceleration cycle back toward the dump at 5 MeV.

CONCLUSION AND OUTLOOK

The longitudinal beam dynamics of the MESA ERL have been optimized through multi-parameter adjustment of the RFCA voltages, phases, R_{56}, and path-length settings across all recirculation arcs. The optimization exploits non-isochronous arc transport and off-crest RF acceleration to control the longitudinal phase space evolution over four accelerating and four decelerating passes. The optimized lattice delivers a 105 MeV beam at the MAGIX interaction point with an rms relative momentum spread of $\sigma_\delta \approx 8 \times 10^{-5}$, satisfying the experimental resolution requirement of $\Delta E/E \leq 10^{-4}$. The longitudinal phase space evolution, including the S-shaped distortion observed at the MAGIX target, reflects the combined effect of RF nonlinearities and dispersive transport. In future work, we will focus on the use of T_{566} to improve the longitudinal beam quality at the interaction point, thereby supporting an even smaller effective energy spread at the MAGIX target and thereby enhancing the overall spectroscopic performance.

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