GSI REPORT 2026-2

GSI-FAIR EARLY-CAREER SCIENTIST REPORTS 2025

PhD and Master student reports
of the division Accelerator Operations and Development

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1. Machine Studies at the ESR

Head: B. Lorentz

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1.1 Motivation

The ESR, as a decelerator and storage ring, covers a broad spectrum of ion species and energies for various experiments [1]. Improving the deceleration efficiency will open up a whole new range of experimental possibilities for the future. For this purpose in the Machine Development (MD) 2024, first measurements were carried out to characterize beam losses during deceleration. There, the closed orbit (CO) was measured throughout the entire cycle, showing significant CO swings during the ramp. These CO swings indicate an asynchronization between the ESR cavities and magnets, which results in a continuous change of $\delta p/p$ over the deceleration ramp. A later analysis of the data has shown, that determining $\delta p/p$ as a function of time, requires a more accurate knowledge and description of the present machine and its optical functions, especially of the Dispersion [2]. Therefore, in the MD 2025 a major focus on beam optics to improve the lattice model has been undertaken [3]. This included measuring the horizontal Dispersion at the position of the 12 Beam Position Monitors (BPMs).

1.2 Method

At each BPM the measured CO, X_{CO}, can be described as a composition of an initial CO distortion, X_0, due to small perturbations in the lattice and a dispersive term, $D_x(s) \times \delta p/p$, namely $X_{CO}(s) = X_0(s) + D_x(s) \times \delta p/p$. The Dispersion is therefore obtained with the difference in CO divided by the difference in $\delta p/p$, which in case of nonlinearities can be composed of higher-order terms:

$$D_x(s) = \frac{\Delta\, X_{CO}(s)}{\Delta\,(\delta p/p)} = D_{x,0}(s) + D_{x,1}(s) \times \delta p/p + D_{x,2}(s) \times (\delta p/p)^2 + \dots \qquad (1)$$

1.3 Measurement Procedure

The CO of the beam was stored at injection energy for several $\delta p/p$ by changing the frequency of the cavity.

1.4 Results

The left-hand side of Figure 1 shows the measured Dispersion at the position of the BPMs. Looking at one BPM, each point represents the Dispersion resulting from a different $\Delta(\delta p/p)$. If the Dispersion would be independent of $\delta p/p$, each curve would be constant, but instead here they can be fitted with a polynomial function, which reveals the existence of high order terms of the Dispersion. For reference on the right-hand side the square markers show the zero order Dispersion, $D_{x,0}$, at each BPM from the nonlinear fit, see Equation 1.

Note that the first 2 BPMs break the ESR symmetry, because they are so much off compared to the rest, but the origin of it is not clarified yet.

1.5 Outlook

High order Dispersion might have an impact on the deceleration bucket and ultimately on the deceleration efficiency. Therefore, the measurements need to be repeated for different energies along the cycle to check for changes in the Dispersion terms and incorporate possible differences into the deceleration studies.

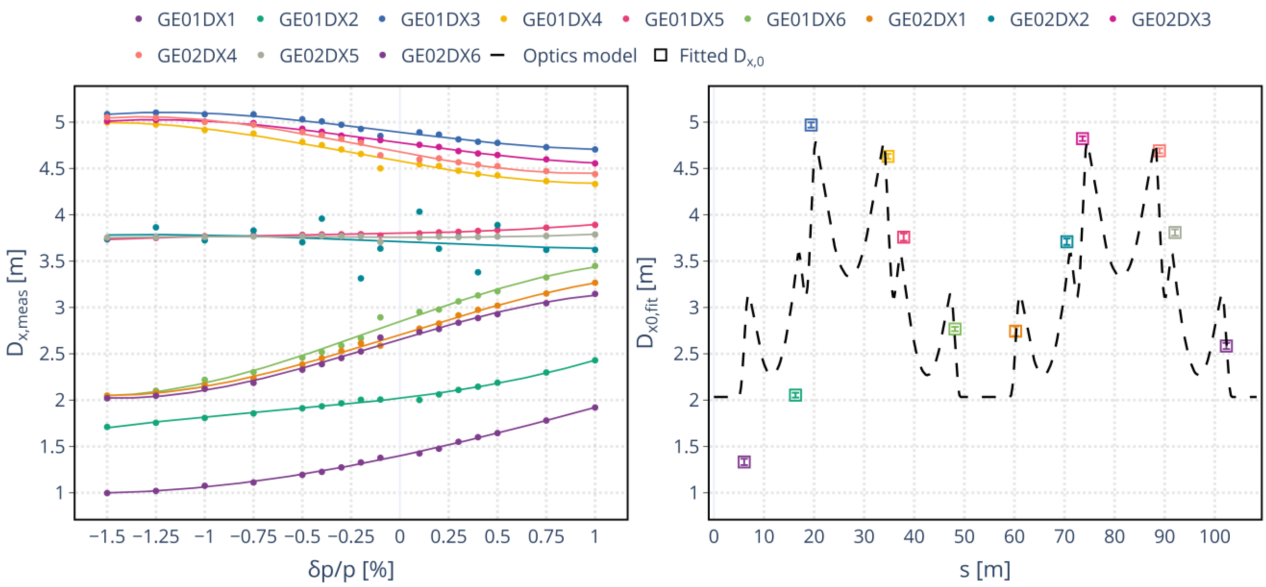

Figure 1: Left: Horizontal Dispersion as measured at the 12 BPM positions. Each point symbolizes the Dispersion as computed from eq. 1 for different $\delta p/p$. Right: For comparison, the theoretical Dispersion from the optics model (black) and the Dispersion $D_{x,0}$ (square) from a nonlinear fit are also depicted.

2. Beam Optics Studies at the ESR

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2.1 Problem Statement

The goal of the measurement campaign was to acquire experimental data that can be used to reduce the existing deviations between simulated and measured betatron tunes at the ESR.
As an illustrative example, one measurement yielded horizontal and vertical tunes of

Q_x = 2.2972
Q_y = 2.2260

whereas the corresponding simulation predicted

Q_x = 2.3511
Q_y = 2.3073.

This results in tune deviations of

ΔQ_x = 0.0539
ΔQ_y = 0.0813

which correspond to relative deviations of approximately 3%.
The data obtained from the measurement campaign were used to determine scaling factors for the ESR quadrupole strengths in order to reduce these tune deviations to values on the order of 0.01 or below.

2.2 Theoretical Basis

A proper understanding of the present problem requires the relation between the betatron tune and the quadrupole focusing strength.
The betatron tune is defined as

$$Q = 1/(2\pi) \oint_C \beta^{-1}(s)\, ds \quad (2)$$ [4].

In the linear (small-perturbation) approximation, a change in the quadrupole strength Δk produces a tune shift

$$\Delta Q = \frac{1}{4\pi} \beta \, \Delta k \, L \quad (3)$$ [5],

where β is the beta function at the quadrupole position and L is the quadrupole length.
The normalized quadrupole strength is defined as

$$k = 1/(B\rho) \quad (4)$$

where Bρ = p / q denotes the magnetic rigidity.

2.3 Measurements

Equation (3) provides a straightforward method for optimizing the quadrupole strengths.
By performing tune measurements for different quadrupole settings, the measured tune shifts can be related to the corresponding changes in quadrupole strength. This makes it possible to determine effective beta functions at the quadrupole locations. During the measurement campaign, each ESR quadrupole family was varied individually by approximately ±2%

around its nominal strength. For each family, ten different k-values within this range were tested. For every setting, three tune measurements were performed. In total, this resulted in approximately 300 measurements.

This systematic variation enables a direct comparison between measurement and simulation and allows the determination of effective scaling factors for the quadrupole strengths.

2.4 Results

The quadrupole scaling factors were determined using the Differential Evolution (DE) algorithm, a population-based global optimization method. DE is a derivative-free optimization technique and is robust against convergence to local minima [6].

By applying this method to the measurement data, the simulated optics model was adjusted to better represent the actual machine. The improvement achieved by this optimization is summarized in Table 1.

	Before Correction	**After Correction**
$\|\Delta Qx\|$	*0.0542*	*0.0002*
$\|\Delta Qy\|$	*0.0810*	*0.0003*

Table 1: Comparison of simulation and measurement before and after applying correction factors to the ESR quadrupoles.$|\Delta Q|$ denotes the absolute difference between measured and simulated tunes.

A more detailed description of the data analysis and optimization procedure can be found in the author's Master's thesis [7].

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