EXPLORATION OF BEAMLINE CONFIGURATION SPACE FOR IDENTIFYING ROBUST QUADRUPOLE CONFIGURATIONS

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Abstract
Experimental beamlines often are regularly reconfigured to meet changing requirements of the experiments and to minimize beam losses. The configuration is usually done with the help of beam optics tools like MADX. These tools offer matching capabilities which allow to find solutions in terms of quadrupole strengths. However, such solutions are found by satisfying the given constraints only and do not take into account limited precision of actual quadrupole devices. Under the influence of quadrupole errors due to magnetic hysteresis, power converter trips etc, the original beamline optics often degrades. This results in beam losses or loss of focus at the experimental target. Readjustment of the optics costs valuable experiment time. Hence, it is desirable to operate a beamline configuration which not only meets the requirements but is also robust against quadrupole errors. Such a configuration will deviate from its nominal properties only by a small margin even when the quadrupole strengths deviate within specified intervals. We present the systematic exploration of beamline configuration space to identify robust configurations. The results are discussed for the BIGKARL beamline at Forschungszentrum Jülich and the findings are supported by experimental data.

INTRODUCTION
Multipurpose beamlines, which provide beams to multiple target stations, are usually underconstrained in terms of the feasible quadrupole settings. This means that a beamline has more degrees of freedom (the quadrupoles’ strengths) than necessary to achieve the desired Twiss parameters at a target or stripper. Because of this, there are many solutions for the quadrupole setting which satisfy the constraints imposed by the desired beamline performance. The main purpose of the beamline is to provide specific Twiss parameters at its end, but additional constraints must be imposed on the beam size along the beamline in order to minimize losses. These additional constraints strongly limit the available parameter space but, usually, many configurations can still satisfy them.

In this work, we explore the feasible parameter space of a particular beamline at Forschungszentrum Jülich. This beamline serves the BIGKARL experimental area and has an overall length of about 40 m (considering only the BIGKARL-specific branch). It consists of twelve quadrupoles with arbitrary polarity. The first four quadrupoles have individual power supplies and among the remaining eight quadrupoles there are four pairs distributed in two bracketing patterns (Q45, Q46 and Q48, Q49) as can be seen from the labels of Fig. 1a, which shows the range of $K_1L$ values for a dataset of 2500 configurations satisfying the imposed constraints. Thus, there are eight degrees of freedom in terms of the power supplies.

The motivation for this study is the fact that multipurpose beamlines must often change their quadrupole configuration in order to allow beam transfer to different target stations. Therefore, the magnetic hysteresis, if not canceled, will affect the actual strength of quadrupoles. Also, other effects like thermal drifts of power converters play a role. The additional effort required from machine operators to fine-tune a beamline setting, even if it is identical to a setting that has been successfully used in the past, is a common problem. A robust configuration will minimize the time operators must spend on fine-tuning the optics. The concepts applied in this study belong to the field of robust optimization which is present across many disciplines [1, 2]. Similarly to a previous study, which was performed for a GSI beamline [3], this study uses large-scale Monte Carlo simulations in order to evaluate the robustness of many possible quadrupole configurations. The findings from simulations are verified experimentally.

ROBUSTNESS
The quadrupole magnets can be set to any value within a range determined by the power supply and maximum current which can be handled by the coil. The normalized strength of the $i$th quadrupole, $K_{1,i}$, lies therefore in an interval: $\{K_{1,i} | K_{1,i,min} \leq K_{1,i} \leq K_{1,i,max}\}$. The space of all possible quadrupole configurations makes up the problem domain $D$. A beamline configuration naturally has to satisfy a set of requirements, e.g., minimal beam losses and focus at the experimental target. The problem domain $D$ will likely contain many different configurations which satisfy these requirements and the subspace consisting of those satisfying configurations is denoted with $S \subset D$. The shape of the subspace $S$ is not obvious due to the nonlinear behavior of the beamline optics in dependency on the quadrupole strengths. The influence of the quadrupole errors on the beamline optics determines its robustness with respect to the given beamline constraints. The specific distribution of quadrupole errors might be different from case to case. Without loss of generality, for a configuration $c_j \in S$, we denote the the space of all possible variations that emerge from the assumed error distributions as $V_j \subset D$. The shape of the subspace $V_j$ might be a box or ball around the original configuration $c_j$, but the particular shape is of no importance for the further discussion. Then the robustness of the configuration $c_j$ can be defined as:

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robustness = \frac{|\mathcal{V}_j \cap S|}{|\mathcal{V}_j|} \quad (1)

where $|\cdot|$ denotes the volume of the given subspace. That is, the fraction of satisfying variations in $\mathcal{V}_j$. This definition of the robustness is bounded by the interval $[0, 1]$ where a value of 1 implies robustness against all possible combinations of quadrupole errors. For practical purposes, the robustness of a given configuration can be evaluated via Monte Carlo simulations.

A configuration that is close to the boundary of $S$ will have low robustness since its variations $\mathcal{V}_j$ reach beyond that boundary. When configurations are obtained via Levenberg-Marquardt algorithm (LMDIF) from MADX [4] by using the desired beamline constraints, they will not be robust by default, because LMDIF stops as soon as those requirements are satisfied, resulting in a configuration which lies close to the boundary of $S$. For example, if the beta function at the target, $\beta$, is specified to be smaller than a threshold $\beta_T$, i.e., $\beta \leq \beta_T$, then LMDIF will end up with $\beta \leq \beta_T$. In order to improve such a configuration in terms of its robustness it is necessary to increase its distance to the boundary of $S$. An effective method is to perform a second LMDIF run with stronger constraints, starting from the previously found configuration. For example, this second run could use $\beta = 0$ as a constraint. Since the new constraints are too strong to be satisfied, the second LMDIF run will converge to a local yet nonzero minimum (or it will fail). This local minimum represents a compromise between all imposed constraints in terms of their mean squared error (which is the cost function used by LMDIF). The further decreasing of the beta function at the target might increase the beta function along the beamline. Therefore, in order to not invalidate the new configuration in terms of its beta functions along the beamline, it is important to keep an extra margin during the first LMDIF run, i.e. $\beta \leq (1 - m)\beta_{\text{beamline}}$ with $0 < m < 1$ for the beta functions along the beamline. Also, since LMDIF minimizes both, horizontal and vertical, beta functions at the target, it is possible that it trades one dimension for the other, for example, decreasing $\beta_x$ while increasing $\beta_y$, but still reducing the overall cost function. This can lead to final configurations which are not satisfying, but they can be rejected since they infringe the original constraints.

**Identifying Robust Configurations**

Large-scale Monte Carlo simulations are performed where each attempt uses a randomly sampled initial quadrupole configuration. The two LMDIF runs are performed to yield a candidate configuration. The first run uses a 10% margin for beta functions along the beamline, i.e., $m = 0.1$. Figure 1b shows the range of beta function values of the candidate configurations. The robustness of these configurations is evaluated by generating 5000 random, uniformly distributed quadrupole errors. They form an $n$-ball ($n=8$) with radius $\Delta K_1 = 1 \times 10^{-3}$ m$^{-2}$ and robustness is computed as the fraction of configurations which satisfy the original constraints.

Figure 2 shows an example for beam size variations at the target. The original configuration lies close to the boundary of $\beta_y$ and many of the variations reach beyond that threshold, leading to a robustness of about 0.5. Figure 3 shows the distribution of robustness scores for all candidate configurations as a histogram. The peak around 0.5 corresponds to configurations which lie close to the threshold for one of the target beta functions. A number of configurations have robustness $\geq 0.99$, so they are robust within the investigated stability radius.
introduced and the resulting beam size variations have been measured. Configurations with high robustness are expected to yield beam size variations which are comparable to the baseline fluctuations. Figure 4 shows the measured beam sizes for a configuration with low robustness, and Fig. 5 shows data for a configurations with high robustness.

Figure 4: Measured beam size variations for a configuration with low robustness.

Figure 5: Measured beam size variations for a configuration with high robustness.

Figure 2: Simulated beam size variations under the influence of quadrupole errors. The beam size of the original configuration is denoted by the black cross. Other points indicate the beam size of a random variation of the original configuration. The variations are uniformly distributed inside a ball with radius $\Delta K_1 = 1 \times 10^{-3} \text{ m}^{-2}$. Example thresholds for the horizontal and vertical beam size are indicated by the dashed lines. The robustness is the fraction of green points that lie inside the threshold bounding box.

Figure 3: Histogram of the distribution of robustness scores among all 2500 satisfying configurations in the data set.

EXPERIMENT

The COSY synchrotron provides beam to the BIGKARL beamline via stochastic slow extraction [5] where the beam’s momentum distribution is blown up by adding noise via the RF-system. The nonzero chromaticity causes particles to be driven into the resonance. This type of extraction implies that the optics of the synchrotron do not change during extraction and the momentum spread of extracted particles is small ($\approx 5 \times 10^{-4}$).

For each configuration, a baseline has been measured. During this baseline measurement no parameters of the beamline were varied and, thus, it represents the natural fluctuations of the beam size. Following the baseline measurement, perturbations of quadrupole strengths have been

CONCLUSIONS & OUTLOOK

The influence of quadrupole errors on the performance of beamlines is a common problem. A quadrupole setting is robust when the beam parameters, for instance beam size on the target, diverge minimally under the errors. We used Monte Carlo simulations to assess the beamline robustness. Dedicated measurements to compare beamline configurations of different robustness confirm the findings.

Further improvements in the computation of robust configurations are discussed in [6], including an analytical approximation of the robustness using Twiss parameters. However, due to the many quadrupoles involved and their nonlinear effect on the beam optics, Monte Carlo simulation must be used to verify any promising configurations.
REFERENCES


