HORIZONTAL PHASE SPACE SHAPING FOR OPTIMIZED OFF-AXIS INJECTION EFFICIENCY

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Abstract

Injection efficiency requires careful monitoring and optimization to maximize the rate of injected current per cycle during refill and minimize the radiation dose and activation of the elements located in the injection region of the accelerator. With the recent introduction of top-up operation at the ESRF, an excellent injection efficiency becomes even more relevant as it is mandatory to reduce as much as possible any kind of perturbation seen by the users. In this paper, we present a novel technique to improve injection efficiency by shaping the horizontal beam phase space to better match the accelerator acceptance for off-axis injection.

INTRODUCTION

At the ESRF, injection into the storage ring is performed in the horizontal plane using a combination of three septum magnets [1]. They provide the final deflection aligning the injected beam along the trajectory of the stored beam with an offset of approximately 20 mm. Finally, this offset is partially cancelled by a local orbit distortion generated by four fast orbit kickers [2]. Significant effort was made to improve the injection efficiency, however even thought an efficiency close to a 100 % was reached in some cases [3] it is generally limited to approximately 80 % during normal operation. The recent introduction of top-up operation motivated renewed interest in improving this figure.

As shown in past studies the transverse phase space or profile can be shaped using non-linear fields and was used for various applications such as the ones presented in Refs. [4, 5] for example. However these studies either focused on reducing the horizontal beam size or shaping the tranverse x-y profile into a uniform distribution. In this paper we present a novel method to tailor the horizontal phase space using sextupolar fields in order to match as well as possible the fraction of the acceptance ellipse available for off-axis injection.

INJECTION MATCHING

As opposed to on-axis injection, for off-axis injection the optimum β-function at the end of the transfer line does not correspond to the β-function of the stored beam. Under the assumption of perfectly linear motion and in the case where $\alpha_i = \alpha_s = 0.0$ and $D_i = D_s = 0.0$ (i and s stand for injected and stored beams, α is the Twiss parameter and D the dispersion) which is true at ESRF, it was shown that the optimum β-function at the exit of the transfer line has to fulfill the following condition [6]

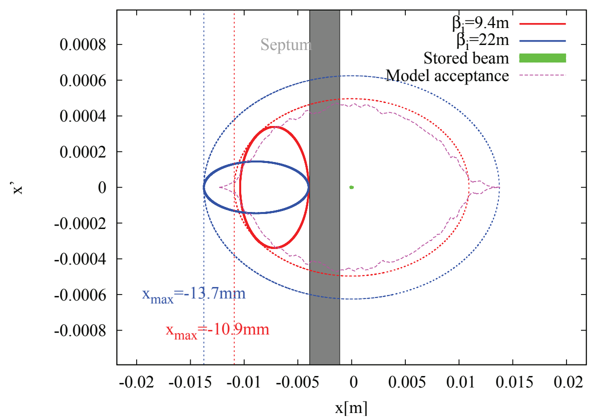

Figure 1: Matched and optimized injected beam for ESRF upgrade parameters. The dashed lines represent the required and modeled acceptances. The stored and injected beams are represented by their 3σ envelopes.

$$3\frac{\beta_i^2}{\beta_s^2} + 2\frac{N_s\sqrt{\epsilon_s\beta_s} + S_w}{N_i\sqrt{\epsilon_i\beta_s}}\frac{\beta_i^{3/2}}{\beta_s^{3/2}} = 1, \tag{1}$$

where N_s is the number of stored beam standard deviations that is left between the septum blade and the stored beam to avoid losses on the septum, N_i is the number of injected beam standard deviations that should be accommodated inside the acceptance, S_w is the width of the septum blade and ϵ is the emittance.

Equation 1 is solved numerically. At ESRF, we have $\beta_s = 38$ m and $S_w = 3.0$ mm. Solving Eq. 1 we find an optimum value for β_i of 17.25 m which is consistent with the operational value of 16 m empirically found by tuning the transfer line based on injection efficiency measurements [7].

A new lattice [8] was developed for the ESRF upgrade which should reduce the horizontal equilibrium emittance to 135 pm [9]. The injection cell was modified to optimize the dynamic aperture and the optimum β_s was found to be approximately 22 m. In this case the optimum horizontal β-function at the exit of the transfer line is $\beta_i = 9.4$ m. Figure 1 represents the injection with β_i matched to the storage ring optics and optimized β_i for ESRF upgrade parameters: properly optimizing β_i allows for a significant gain of 2.8 mm in maximum horizontal excursion.

Although careful optimization of the optics at the exit of the transfer line allows for significant improvements it is also seen that in the case of off-axis injection the elliptical beam shape in the x-x' phase space does not perfectly match the available acceptance. Introducing a sextupolar field in the transfer line would distort the phase space into a triangular

ISBN 978-3-95450-147-2

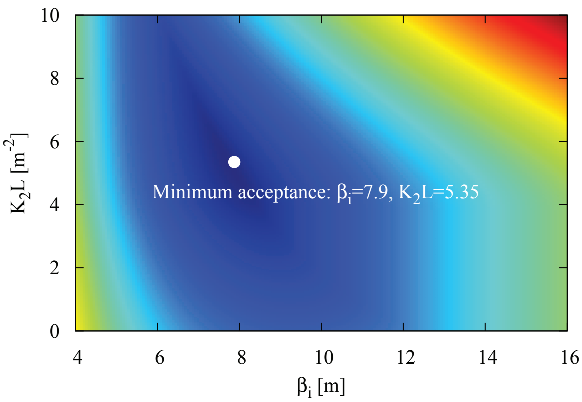

Figure 2: Minimum required acceptance as a function of β_i and K_2L. The color map goes from dark blue, the smallest acceptance, to red, the largest acceptance. The optimum is found for β_i=7.9 m and K_2L=5.35 m^{-2}.

shape and hence, allow for better usage of the available acceptance and further optimize the injection efficiency.

INJECTION MATCHING WITH DISTORTED PHASE SPACE

Introducing non-linear fields makes it difficult to find an analytical solution for the optimum sextupole strength and β-function at the end of the transfer line. However, this problem is easily solved numerically: the β-function of the storage ring being fixed one can determine the minimum required ring acceptance in order to enclose the 3 σ injected beam envelop which is constrained by the sextupole strength and optics parameters at the end of the transfer line. An optimum couple (β_i,K_2L), representing the β-function at the exit of the transfer line and sextupole strength, for which the required acceptance is minimized, can therefore be found.

The results for the case where β at the sextupole is equal to 40 m are shown in Fig. 2. A minimum is found for β_i=7.9 m and K_2L=5.35 m^{-2} which shows that the β-function at the end of the transfer line can be decreased in addition to the better adapted phase space. The overall improvement of the injection efficiency is therefore expected to be a combination of these two effects.

Figure 3 shows a comparison between the fully optimized injection with and without phase space shaping. An effective gain of 1.0 mm in the maximum horizontal excursion is observed in the presence of beam shaping. The optimum parameters for the sextupole field and β-function at the exit of the transfer line were derived assuming a perfectly elliptical acceptance. Taking into account the shape of the simulated acceptance the situation can be slightly improved, as shown on the green curve.

The overall gain can be derived using tracking simulations which result are shown in Tab.1. This was done for various scenarios envisaged for the upgrade program. Although the major steps towards 100 % injection efficiency are the reduction of emittance and a proper matching of the optics functions at the end of the transfer line, the additional few percents improvement from the sextupole beam shaping could allow to achieve a theoretical 100 % injection efficiency for the ESRF upgrade machine.

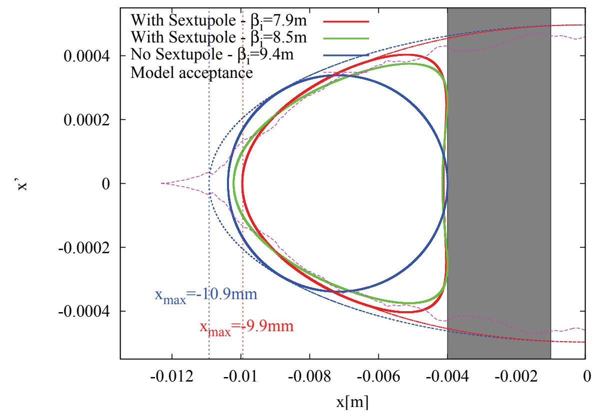

Figure 3: Comparison between optimized injection with and without sextupole phase space shaping.

Table 1: Simulated Injection Efficiencies for the ESRF Lattice with Multipole Errors and Alignment Errors Corrected Averaged Over a 100 Seeds

TL2 sextupole	β_i m	ϵ=120 nm	ϵ=60 nm
0.0 m^{-2}	22.1	56± 2%	79± 1%
0.0 m^{-2}	9.4	79± 1%	92± 1%
6.0 m^{-2}	8.5	82± 1%	94± 1%
5.35 m^{-2}	7.9	83± 1%	95± 1%

EXPERIMENTAL STUDIES

A dedicated transfer line optics including a spare sextupole from the storage ring was developed in order to perform experimental studies on the existing machine. The first test was to commission the new lattice and achieve injection efficiency at least as good as the previous one.

The final results of the commissioning are shown in Fig. 4. The curves on this plot represent the storage ring current normalized by the booster current as a function of the turn

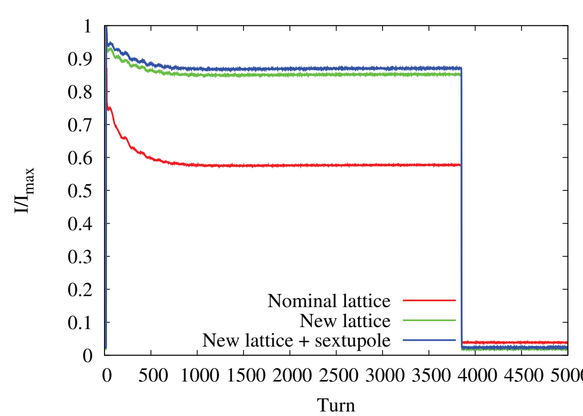

Figure 4: Injection efficiency with new and old optics with sextupole ON or OFF.

ISBN 978-3-95450-147-2

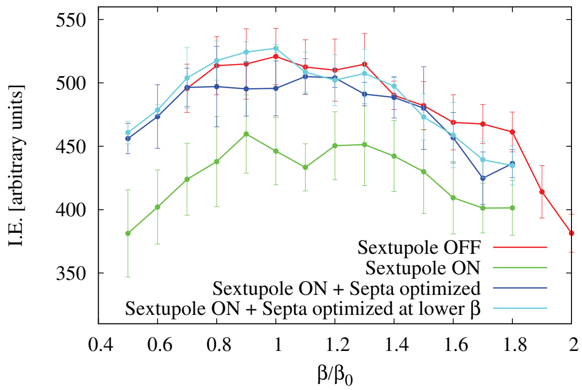

Figure 5: Scans of the horizontal β-function at the end of the transfer line for various configurations.

number after injection. The initial value is normalized to 1. The final value when the current is stabilized is therefore a measurement of the injection efficiency. The new lattice was implemented based on the theoretical model, and changes applied to vertical steerers and septa at the end of the transfer line were sufficient to achieve better than nominal performance. It should be noted that the nominal lattice was not precisely tuned explaining its poor performance in this example. Turning ON the sextupole further improved the injection efficiency by 2 % which is consistent with predictions since in this case the nominal β-function at the end of the transfer line was used not allowing for the optimal gain.

The second experimental test aimed at showing the possibility of reducing the β-function at the end of the transfer line when the sextupole is turned ON. For this purpose, dedicated tuning knobs allowing to change the optics functions independently of the initial condition were developed. Furthermore, the initial steering of the transfer line implies to center the beam trajectory inside the quadrupoles which should help avoiding unwanted trajectory distortion due to the quadrupole field variations. Because of the lack of reliable diagnostics at the time this initial steering was done by hand and small distortions are to be expected. The recent addition of new pick-ups and plans for an automated feedback loop in the transfer line will remove any bias in the analysis. This experimental work should therefore be repeated and confirmed once these systems are operational.

Figure 5 shows the results of horizontal β-function scans for various scenarios. The first thing to note is that the width of the error bar on these measurements is about the size of the effect we would like to observe. However, although not fully conclusive, these results can help understanding some trend and confirm theoretical observations. The red curve represent the case with the sextupole turned OFF β-function at the end of the transfer line and steering initially optimized. β/β_0=1 representing the initial point one can see that the initial tuning was rather effective as no better point was found during the scan. Turning ON the sextupole degraded the situation which was later on recovered by tuning the septa as shown by the blue curve. Finally, reducing the β-function and retuning the septa with the sextupole ON allowed to further improve the situation.

Although the gain with respect to the initial situation without sextupole is hardly visible, the overall behavior seems to confirm theoretical expectation as the optimal point with sextupole ON was found for reduced β-function at the end of the transfer line.

SUMMARY AND OUTLOOK

A novel method to improve off-axis injection efficiency by shaping the horizontal phase space using sextupolar field was presented. Distorting the horizontal phase space into a triangular shape one can achieve a better match of the available acceptance constrained by the septum blade and the storage optics functions. Tracking simulation using the ESRF upgrade machine parameters predict a net gain of 4 %. This method was experimentally studied at the ESRF storage ring and transfer line using a spare sextupole and dedicated optics design. The optics were successfully commissioned and first experimental data appear to be consistent with theoretical predictions. However, it should be noted that at the time, the transfer line was poorly equipped in terms of position measurements and a good control of the trajectory inside the transfer line as required by such experiment was made difficult. Since then, significant efforts have been made in that direction and new pick-ups were installed all along the transfer line, having in mind the development of a trajectory feedback system for the transfer line. Once this system is operational, beam shaping experiments will be resumed and revisited in order to confirm these preliminary results.

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