

INJECTION STUDIES FOR ELETTRA 2.0

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Abstract

A comprehensive evaluation of injection performance for Elettra 2.0 has been conducted to establish high-efficiency, low-perturbation top-up operation in the upgraded ultralow-emittance storage ring. The baseline four-kicker bump injection scheme, utilizing a 4.3 μs half-sine pulse and a -6 mm stored-beam orbit excursion, achieves injection efficiencies up to 100% under nominal conditions. Beyond the baseline performance characterization, the study examines how machine imperfections and operational parameters influence injection efficiency, including wakefield and third-harmonic cavity effects on the injected bunch. The results establish operational tolerances and highlight optimization strategies that improve injection robustness and long-term stability.

INTRODUCTION

Elettra 2.0 is a 259.2 m long fourth-generation light source that will replace the existing Elettra facility [1, 2]. The new storage ring adopts a specially designed multi-bend achromat (MBA) lattice (so called S6BA-E, Symmetric six Bend achromat and enhanced using reverse bends and dipoles with both transverse and longitudinal gradient) designed to achieve ultralow emittance and to meet all the user requirements. The main design parameters are summarized in Table 1 and the optical functions for a single lattice cell are shown in Fig. 1. The strong focusing required by the MBA design restricts the available dynamic aperture, making efficient injection challenging but essential.

Table 1: Key Parameters of the Elettra 2.0 Storage Ring

Parameter	Value	Unit
Beam Energy	2.4	GeV
Circumference	259.2	m
Harmonic Number	432	
Betatron Tunes (H/V)	32.30 / 9.16	
Natural Emittance	238	pm rad
Energy Spread	9×10^{-4}	

The baseline injection scheme uses a four-kicker bump. Four kicker magnets are powered simultaneously to displace the stored beam by -6 mm horizontally. The injected beam from the booster is guided by three septum magnets to a position of -10 mm. After the bump closes, the injected beam undergoes betatron oscillations until radiation damping merges it into the closed orbit. The schematic layout of the injection bump is shown in Fig. 2.

The kickers are driven by a half-sine pulse of approximately 4.3 μs duration. While tracking simulations for the

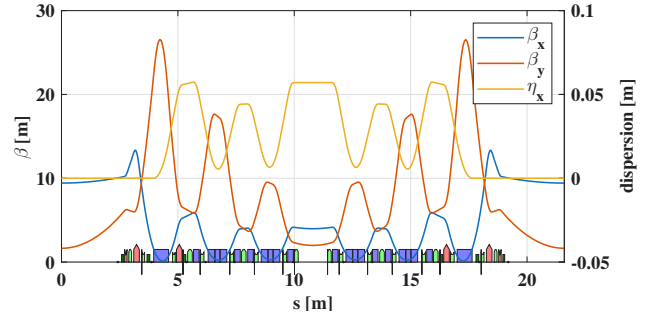


Figure 1: Optical functions (β_x , β_y and dispersion η_x) for one cell of the Elettra 2.0 multi-bend achromat lattice.

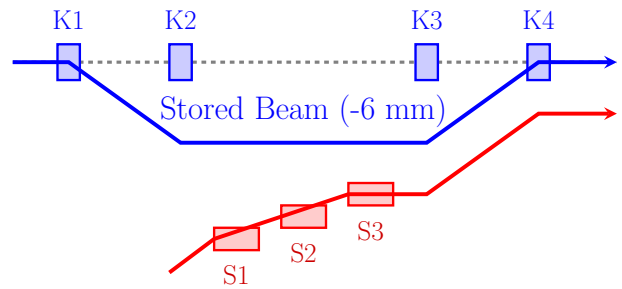


Figure 2: Schematic of the Elettra 2.0 four-kicker injection bump. The stored beam trajectory (blue) is displaced to clear the septum blade, and the injected beam (red) arrives from the booster.

ideal machine predict high injection efficiency, realistic conditions reduce performance. In-vacuum undulators (IVUs) operating at minimum gap restrict the physical aperture, and magnet misalignments and field errors further reduce transmission. This report evaluates the effect of different booster operating modes on injection efficiency, assesses injection tolerances to realistic machine errors, discusses the mitigation of stored beam distortions driven by bump leakage, and analyzes the effects of wakefields and a third-harmonic cavity (3HC) on injection performance. The eLlegant [3] and AT [4] simulation codes were extensively used for these studies.

INJECTION TOLERANCES

Achieving high injection efficiency relies not only on the storage ring layout but also on the injected beam properties. While the storage ring undergoes a full upgrade to Elettra 2.0, the existing booster ring has been refurbished [5]. Detailed information on the booster upgrades is available in [6]. Significant effort has been devoted to tuning the booster to meet the requirements of the new storage ring. As a result, the booster emittance has been reduced from 240 nm to 140 nm at 2.4 GeV [7].

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For an ideal machine, initial simulations predict injection efficiencies approaching 100%. However, the inclusion of realistic machine errors results in a noticeable reduction in efficiency. The booster update also enables operation in different modes, including standard, emittance exchange, and fully coupled (round beam) operation. Injection performance with the booster operating in these three modes has been studied in detail.

To evaluate the performance of these modes, we must first consider the physical aperture constraints of the storage ring. The horizontal aperture, assuming the collimator is fully opened, is limited by the septum blade at -7 mm. In the vertical plane, with the scraper fully opened, the aperture is limited by the in-vacuum undulators (IVUs) to a half-gap of 2.5 mm.

The choice of booster operating mode is based on maximizing injection efficiency while minimizing losses inside the insertion devices. Simulations indicate that both emittance exchange and round beam modes yield comparable injection efficiencies that exceed those of standard booster operation. When machine tolerances are included, the emittance exchange mode shows a tendency for losses to concentrate in the IVUs. For this reason, round beam operation is selected as the preferred booster configuration.

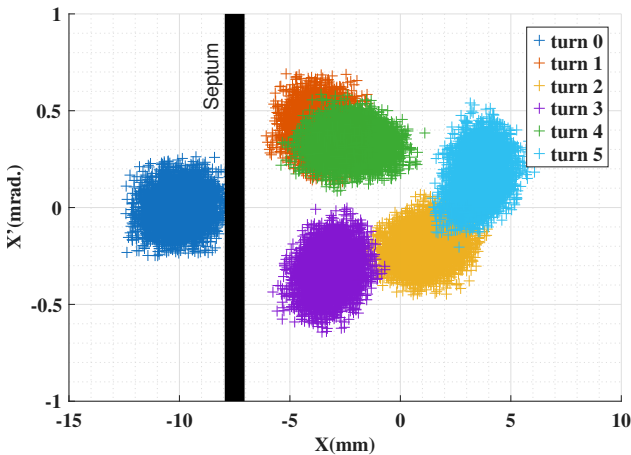


Figure 3: Injected beam phase space over the first five turns at the exit of the final septum (S3).

Figure 3 shows the injected beam phase space in the first 5 turns at the exit of S3. The sensitivity of the injection efficiency to errors in the injected beam position and angle is shown in Fig. 4. A strong asymmetry is observed in the horizontal plane due to the presence of the septum blade. Following the implementation of orbit feedback in the transfer line [6], the orbit stability at the booster-to-storage-ring transfer line exit is better than $100 \mu\text{m}$. The results in Fig. 4 indicate that injection efficiencies above 99% are maintained for position and angle errors of up to $\pm 200 \mu\text{m}$ and $\pm 200 \mu\text{rad}$, respectively.

Although the ideal machine shows close to 100% injection efficiency with the round beam configuration, machine errors will reduce performance in practice. Tolerance studies were performed over 100 random machine instances with

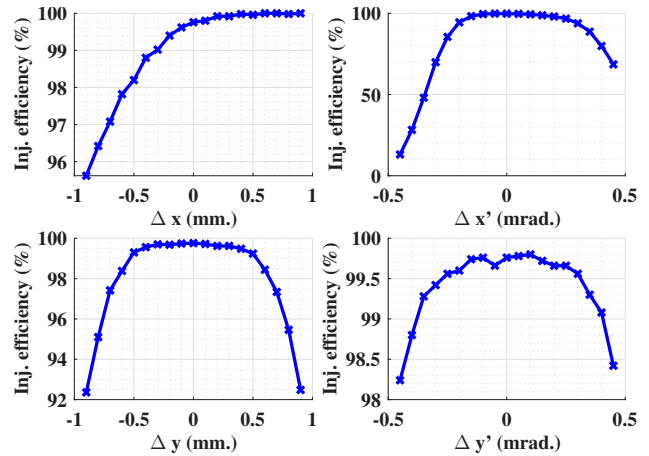


Figure 4: Injection efficiency sensitivity to amplitude and angle. The top row shows the sensitivity to horizontal position (left) and angle (right) errors. The bottom row shows the vertical plane.

normally distributed alignment offsets, roll, and multipole errors. While these simulations did not incorporate the full sequence of expected errors and subsequent active corrections, the applied error amplitudes were specifically chosen to mimic the residual errors expected in the real machine after correction.

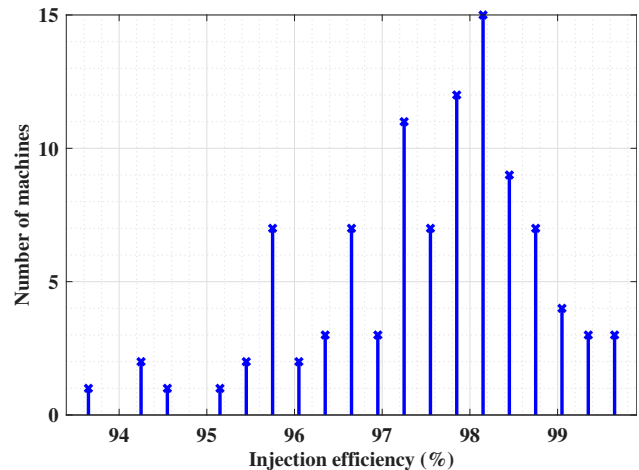


Figure 5: Histogram of injection efficiency evaluated over 100 machines with errors.

Figure 5 shows the histogram of injection efficiency. For the standard $4.3 \mu\text{s}$ kicker pulse, the average injection efficiency across error machines drops to approximately 98%.

DISTORTIONS OF THE STORED BEAM

Measurements at Elettra have shown that the dominant contribution to injection-induced distortions arises from leakage fields of the septum magnets. These fields introduce residual kicks to the stored beam, reaching values of up to $70 \mu\text{rad}$. For Elettra 2.0, this issue has been addressed by adopting a septum design with a composite-material blade, which significantly reduces magnetic field leakage. Based on the design and magnetic modeling, the residual kick to

the stored beam due to leakage fields is expected to be below 1 μrad .

While the new septum design mitigates leakage fields, additional perturbations arise from the imperfect closure of the four-kicker bump. In Elettra 2.0, no multipole elements are present within the injection bump, so the non-closure is primarily attributed to differences in pulsed power supply responses, timing jitter between the kicker magnets, and the coating of the ceramic chambers. Timing jitter was measured to be on the order of 1 ns peak-to-peak. Considering the original 3 μs pulse duration of the kicker magnets, calculations show that this jitter can drive horizontal beam centroid oscillations of up to 200 μm . To mitigate these perturbations, our strategy focuses on optimizing the pulse length and horizontal tune to minimize residual kicks. For the half-sine driving pulse of the kickers, extending the pulse duration to n integer multiples of the revolution period and selecting a horizontal fractional tune of $(1.5 + i)/n$ (where $i \in [0, n - 3]$) effectively suppresses the residual oscillations. By setting $n = 5$, the pulse length becomes 4.3 μs . Combined with a horizontal fractional tune near 0.30, this reduces the expected stored beam centroid oscillations from approximately 200 μm to about 50 μm , even under worst-case 1 ns jitter conditions (see Fig. 6). Distortions arising from the differences in pulsed power supply responses and the coating of the ceramic chambers are reduced similarly.

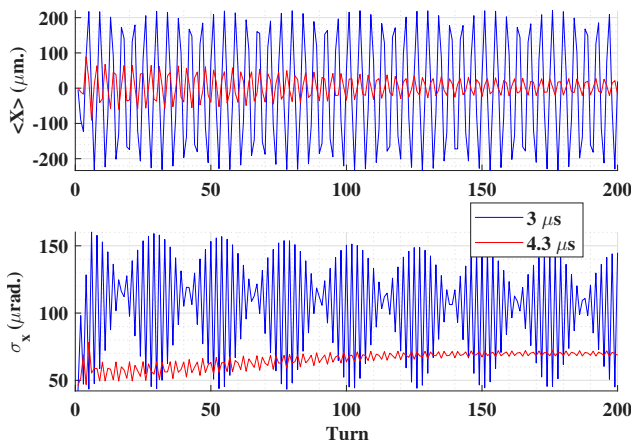


Figure 6: Comparison of stored beam centroid and beam size distortion due to 1 ns peak-to-peak kicker jitter, sampled turn-by-turn.

INJECTION EFFICIENCY WITH HARMONIC CAVITY AND WAKES

To evaluate the impact of collective effects on the injection process, tracking simulations were performed to compare injection efficiencies with and without the inclusion of wakefields and the third-harmonic cavity (3HC). The simulations demonstrate that the wakefields have no observable effect on the injection efficiency, regardless of whether the 3HC is active or inactive. Interestingly, when the 3HC is active (in the absence of wakefields), a slight improvement in injection efficiency is observed. This improvement is highly likely

due to the significantly lower synchrotron tune induced by the 3HC. Because the longitudinal oscillations are much slower, the bunch length translates into an energy spread that contributes to the transverse amplitude via dispersion. This interaction occurs at a point where the transverse oscillations are slightly lower, effectively mitigating losses and enhancing the overall injection efficiency. A comparison of the injection efficiencies under these different configurations is presented in Fig. 7.

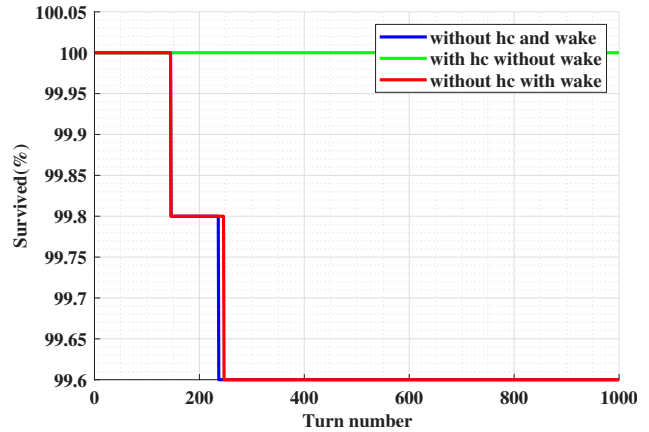


Figure 7: Comparison of injection efficiencies with and without wakefields, and with the 3HC powered on versus off.

CONCLUSION

Tracking simulations have been used to evaluate and optimize the injection scheme for Elettra 2.0. While both emittance exchange and round beam booster operations provide high injection efficiency, the fully coupled (round beam) mode was selected as the preferred configuration to minimize losses inside the in-vacuum undulators. In an ideal machine, this configuration yields an injection efficiency approaching 100%. With realistic machine errors, the average efficiency is approximately 98%.

Perturbations to the stored beam driven by kicker timing jitter are effectively suppressed by extending the kicker pulse duration to 4.3 μs and optimizing the horizontal fractional tune. This reduces the expected horizontal centroid oscillations from approximately 200 μm to about 50 μm .

Finally, collective effect studies indicate that wakefields have no observable impact on the injection process. However, operating the passive third-harmonic cavity provides a slight improvement in injection efficiency by lowering the synchrotron tune.

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