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RELAXED INSERTION REGION OPTICS AND LINEAR TUNING KNOBS FOR THE FUTURE CIRCULAR COLLIDER *

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Abstract

This paper provides updates on two essential toolsets designed to facilitate the tuning and commissioning processes of the Future Circular Collider (FCC): relaxed optics and linear tuning knobs specifically for the experimental insertion regions. Motivated by the imperative need for efficient tuning strategies, we outline the construction methodology for both toolsets and present initial studies demonstrating their efficacy. The paper discusses the significance of these tools in enhancing the operational capabilities of the FCC and presents early results showcasing their potential impact on the collider's performance during tuning and commissioning phase.

INTRODUCTION AND MOTIVATION

The Future Circular Collider (FCC) aims to probe the standard model by colliding electrons and positrons beams with energies ranging from 45.6 to 182.5 GeV [1]. The aim is to obtain precision measurements of the Z, W and Higgs bosons as well as the top quark. To maximize the utility the FCC sets extremely challenging luminosity targets that are achieved through demanding insertion region optics, tight vertical emittance targets, and high beam currents.

Whilst the beam current is limited by the maximum available power supply, both the emittance and optics demand special tools for a precise control in operation and commissioning [2–4]. Moreover, the challenging design can potentially put a high strain on other machine properties such as the dynamic aperture and lifetime when combined with other limiting factors such as magnet and alignment errors or beam-beam effects. Especially during the early stages of commissioning, before applying orbit and optics correction and possible beam-based alignment, the challenging optics may make it impossible to achieve stable orbits.

With this in mind two sets of tools were developed and their utility was explored, namely relaxed insertion region optics and linear optics tuning knobs for the insertion region. The relaxed optics are a set of optics that increase the β functions at the interaction point (IP), β^*, by precisely rematching the strengths of a small set of magnets in such a way that the Twiss functions only change locally in the insertion region whilst remaining completely constant in the rest of the machine. At the same time other optics functions such as the dispersion stay completely unchanged. A larger β^* results in smaller β functions along the rest of the insertion region, making the overall beam dynamics less susceptible to errors and misalignments in the insertion region magnets, reducing the chromaticity and relaxing the crab sextupole. Therefore, such an optics could ease comissioning.

Linear tuning knobs also aim to change optics functions at the IP but are less precise and in this case use a larger set of magnets. These aim to exploit the linear response of optics functions to small changes in magnetic strengths to create linear combinations of changes in strengths in magnet groups that are proportional to desired changes in specific optics functions. Whilst this method is not as precise as the dedicated relaxed optics and results in small perturbations of other optical functions, it allows for an easy adjustment of these parameters during operation, even with limited information of the precise value of the optics functions. This could be used to scan these knobs to improve the luminosity or general performance of the machine as has been done in [5, 6].

RELAXED OPTICS

Method

A plot showing the optical functions in the insertion region for the 45.6 GeV so called Z-lattice (version 23) is shown in Fig. 1 [7]. Figure 1 also highlights in red two dispersion-free regions to the left and right of the IP and located after the crab sextupoles. Due to their location, changing the strength of these quadrupoles does not affect the dispersion outside of this region as well as the phase advance between the IP and the crab sextupoles. For this reason, these magnets can be used to match the relaxed optics.

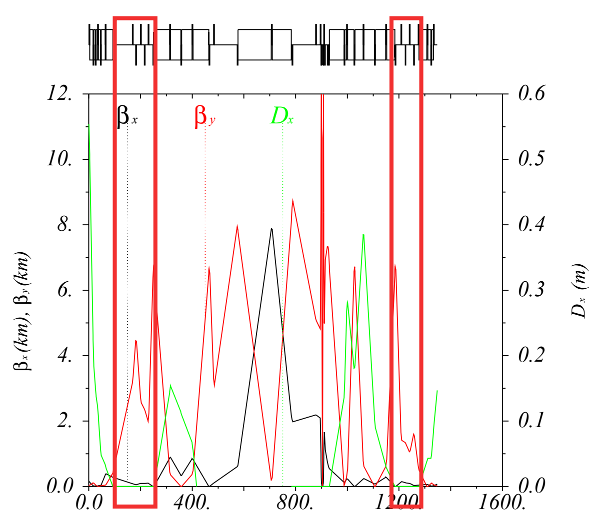

Figure 1: Insertion region design optics for FCC-ee Z-lattice.

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To implement this scheme, a set of MADX macros was written that save key optics parameters of the original lattice and then find the strengths of the magnets to obtain optics in which the horizontal and vertical β^* are scaled by a certain factor using the MADX matching module, whilst preserving the tunes and the optics functions outside of the insertion region. The macros and example scripts were made available in the FCC-ee optics repository so that they are accessible to the community for dedicated studies [7].

To obtain a relaxed optics with the largest possible relaxation factor whilst not affecting tunes, it was found that it was ideal to successively increase the scaling factor in multiple iterations, repeating this until no solution could be found. For each iteration, the magnet strengths are written to a file so that the setting can be recovered in other simulations. This iterative approach also results in strength files for the intermediate solutions that would allow for the simulation of a gradual squeezing of the beam at the IP as well as allowing for iterative correction schemes.

It was found that it was not always ideal to use equal scaling factors for the horizontal and vertical plane so that these parameters can be changed independently. To allow for this, the scaling factor can be changed independently in the matching scripts. Since the chromaticity from the final focus system is only partially corrected locally, relaxed optics results in an overcorrected chromaticity from the arc sextupoles. When used in practice it is therefore crucial to rematch the arc sextupole strengths to obtain the correct chromaticity. A simple way of doing this is by equally adjusting the strengths of all focusing and all defocusing arc sextupole families to obtain the original chromaticity. However, this might have an impact on the dynamic aperture, so a full optimisation could also be considered.

Result

The scripts outlined above were applied to the version 23 z-lattice, achieving a total relaxation factor of 3.1 and 1.8 in the horizontal and vertical planes, respectively. The final un- and over-corrected chromaticity is 155 and -14 in the two planes, whilst the tune remains unchanged. The results are shown in Fig. 2. Similarly, a total relaxation factor 2.6 and 1.6 can be achieved for the 182.5 GeV tt-lattice and similar results were obtained for previous versions of the lattices.

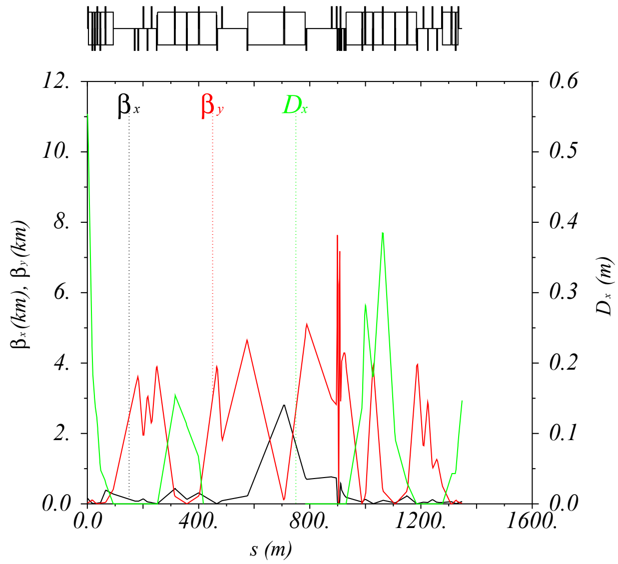

Figure 2: Relaxed insertion region design optics for FCC-ee Z-lattice.

TUNING KNOBS

Method

In order to control the luminosity in the various IPs it is important to have a tight control on the location and magnitude of the minimum β-function, at the so-called betatron waist. In particular, the displacement between the waist and the IP, w, and the size of the β-function at this location, β_w, have to be tune-able. These parameters relate to IP β^* and α^* as $\beta_w = \frac{\beta^*}{(1+\alpha^{*2})}$, $w = -\frac{\alpha^*\beta^*}{(1+\alpha^{*2})}$.

In a first attempt to create knobs for these parameters, similar scripts for rematching the IR as for relaxed optics were written, using the same quadrupoles. These scripts aim to change one of the waist parameters at a time whilst keeping the other parameters constant and ensuring compatibility with the rest of the machine. Using these scripts, four values of each waist parameter were matched and a linear fit was applied to the strengths of each quadrupole, allowing the interpolation or extrapolation of the quadrupole strength settings for any desired waist parameter [8].

The derived knobs resulted in a linear response in the desired parameter but quadratic responses in the parameters that were supposed to remain unchanged. To further reduce these aberrations and obtain a larger region over which the knobs are effective, more points can be matched and a higher order fit can be used, resulting in non-linear knobs. Although effective, these knobs may be more complicated to implement in a control room environment.

An alternative option that is known to reduce aberrations and therefore increase the effectiveness of the knobs is described in [9]. This method uses singular value decomposition (SVD) of the response matrix from quadrupole changes to find the pseudo inverse and hence come up with knobs that are also linear. In the first step of this method, the strength of each quadrupole, k_j, in the dispersion free region of the IR and in the final focus doublet is modulated by one percent individually and computing the global Twiss using cpymad. The resulting change in various observables, o_i, including the shift in the waist location, the relative change in β_w, and the change in the global tune, is recorded to construct a response matrix $\mathbf{M}$ as $M_{ij} = \frac{\Delta o_i}{\Delta k_j/k_j}$.

This response matrix can be decomposed using SVD as $\mathbf{M} = \mathbf{USV}^T$, this can be done using linear algebra packages such as that in numpy [10]. A pseudo-inverse of the response matrix can be obtained by computing $\mathbf{VS^{-1}U}^T$ and the relevant knob can be obtained by multiplying a vector consisting of 1 in the row corresponding the desired observable and zeros in all other rows. This method has the added benefit that

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it allows for a regularisation of the results by truncating the **S** matrix, either by keeping only a set fraction of the obtained singular values or by eliminating all singular values below a pre-set threshold. This regularisation avoids correlated or degenerate quadrupoles to result in large strength settings.

Result

The SVD method was applied to z-lattice to find knobs for w and β_w in both planes. An example of a resulting knob for the vertical waist w_y is shown in Fig. 3 over ± 4 cm, which shows the actual vertical waist position vs. the knob setting, showing a good linear agreement. Figure 3 also shows the horizontal waist position for every setting, which varies much less and in a quadratic way, as expected. Similarly, the horizontal β_w does not change significantly, however, there is a larger impact on the vertical β_w as can be seen in Fig. 4.

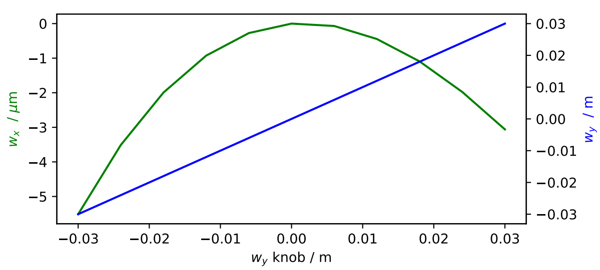

Figure 3: Horizontal and vertical waist location for vertical waist knob setting in Z lattice obtained from SVD.

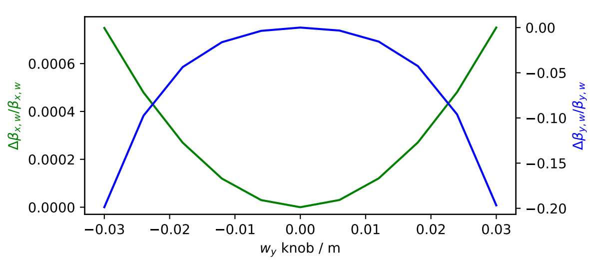

Figure 4: Horizontal and vertical β_w for vertical waist location knob setting in Z lattice obtained from SVD.

The range of the knobs is limited by the change in tune resulting from the various settings, which results in the global machine reaching resonance conditions. This could be countered by simultaneously rematching the tune using the arcs or the radio frequency cavity insertions. Without doing this, the effective range of the knobs for these three parameters is summarised in Table 1, which also shows the change of the other observables at these extremes. The results in Table 1 show that these knobs give a significant range on the waist parameters for a good control of the luminosity, whilst keeping the other parameters unchanged.

This method can easily be extended and improved by adding further observables and quadrupoles. For example by adding the quadrupoles in the dispersion suppressors to the left and right of IP and also observing the chromaticity, a knob for the horizontal dispersion in the IP with a range

Table 1: Knob Ranges for β Waist Control and Perturbation of Other Parameters

Knob	**Range**	**Perturbation**			
		$\frac{\Delta\beta_{w,x}}{\beta_{w,x}}$	$\frac{\Delta\beta_{w,y}}{\beta_{w,y}}$	$w_x/\beta_{w,x}$	$w_y/\beta_{w,y}$
$\frac{\Delta\beta_{w,x}}{\beta_{w,x}}$	40%	-	<1%	0.8%	<0.1%
$\frac{\Delta\beta_{w,y}}{\beta_{w,y}}$	20%	<1%	-	0.06%	12%
w_x	40 cm	30%	2%	-	1.2%
w_y	3 cm	<1%	20%	0.06%	-

of ± 2 mm can be constructed, as well as a ± 0.01 for the derivative of the dispersion. Similarly, by introducing skew circuits in these quadrupoles and also observing the global coupling, a knob for the vertical dispersion and its derivative can be constructed with a range of ± 0.6 mm and ± 0.1 respectively. The effectiveness of this method for FCC-ee is further explored in [11].

FIRST APPLICATIONS AND OUTLOOK

The relaxed optics have been used in various studies, for example it has been shown that in a lattice with effective errors, the dynamic aperture is marginally improved using an intermediate relaxed optics and a chromaticity correction achieved by scaling the arc sextupoles [12, 13]. However, it then decreases in the maximally relaxed optics. This is most likely due to the un-optimised sextupole settings and would be significantly improved once they are re-optimised and the crab sextupoles strengths are adjusted. The vertical emittance for uncorrected lattices does not decrease significantly when applying relaxed optics [14], however, the optics have been used in orbit correction studies to make it possible to find closed orbits with large errors [15]. Future improvements to the scheme, including rematching of the IR and arc sextupoles would most likely make this more effective.

The waist knobs have been successfully tested with luminosity simulations using the X-Suite beam-beam module [16] in unperturbed lattices, performing as expected. In the close future the plan is to extend this method to more realistic simulations that include errors and other components such as tilted solenoids and beam-beam effects, attempting to improve the realistic tuning of the machine. The knob creation method can be readily expanded to more observables to have better control of the machine.

CONCLUSION

Tools to effectively create relaxed optics and IP tuning knobs have been developed and made available to the broader FCC-ee community. These tools are flexible and adjustable to future needs and design iterations. Some first studies using these tools have been performed with many potential use cases to follow.

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