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UPDATED MONOCHROMATIZATION INTERACTION REGION OPTICS DESIGN FOR FCC-ee GHC LATTICE

A. Korsun*, A. Faus-Golfe, Z. Zhang†, CNRS/IN2P3 IJCLab, Univ. Paris-Saclay, Orsay, France
F. Zimmermann, CERN, Geneva, Switzerland
P. Raimondi, FNAL, Batavia, US
K. Oide[2], Geneva University, Geneva, Switzerland
[2]also at KEK, Tsukuba, Japan

Abstract

Determining Yukawa couplings of the Higgs boson is one of the most fundamental and outstanding measurements since its discovery. The FCC-ee, owing to its exceptionally high-integrated luminosity, offers the unique opportunity to measure the electron Yukawa coupling through *s*-channel Higgs production at 125 GeV centre-of-mass (CM) energy, provided that the CM energy spread can be reduced from 50 MeV to a level comparable to the Higgs bosons' natural width of 4.1 MeV. To improve the energy resolution and reach the desired collision energy spread, the concept of a monochromatization mode has been proposed as a new operation mode at the FCC-ee, relying on the Interaction Region (IR) optics design with a nonzero dispersion function of opposite signs at the interaction point (IP). A first optics design and preliminary beam dynamics simulations have been carried out for V22 of the FCC-ee GHC lattice type. In response to the continuously evolving FCC-ee GHC optics, this paper presents the first updated monochromatization IR optics design based on V23 of the FCC-ee GHC optics.

INTRODUCTION

The FCC-ee collider is primarily designed for four main energy configurations: 45.6, 80, 120, and 182.5 GeV per beam, targeting precision studies at the Z-pole (Z), W-pair production threshold (WW), Higgsstrahlung peak (ZH), and top-quark pair production threshold (ttbar mode). A fifth mode has also been proposed: direct s-channel Higgs production at a CM energy of 125 GeV, known as monochromatization mode. This enables probing the electron Yukawa coupling by directly producing the Higgs boson in the s-channel. Achieving this requires reducing the CM energy spread, mainly caused by synchrotron radiation, from about 50 MeV to approximately 5–10 MeV, comparable to the Higgs boson's natural width [1-4].

This reduction can be realized using a "monochromatic" collision scheme, a decades-old concept introducing correlations between particle energy deviation and transverse position at the IP. This effectively lowers the CM energy spread without necessarily altering the individual beam energy spreads [5-16]. Practically, this is achieved via opposite-sign horizontal or vertical dispersion at the IP for the two beams, a technique known as transverse monochromatization. While effective, it increases transverse beam sizes at the IP and may influence the achievable luminosity. The interplay between dispersion and luminosity can be described using the monochromatization factor:

$$\lambda = \sqrt{1 + \sigma_\delta^2 \left(\frac{D_x^{*2}}{\varepsilon_x \beta_x^*} + \frac{D_y^{*2}}{\varepsilon_y \beta_y^*}\right)} \quad (1)$$

This factor quantifies the reduction in both CM energy spread and luminosity relative to the standard collision mode. Consequently, the design of an effective monochromatization scheme must include a careful optimization of beam optics and other collider parameters to sustain sufficient luminosity while ensuring a narrow energy spread, crucial for enhancing the rate of Higgs production in the *s*-channel [17]. Besides, at high energies, as in the case of FCC-ee, the effects of beamstrahlung (BS) [18] must be taken into consideration. Furthermore, crossing angle and hour-glass will also be taken into account [19-24].

The monochromatisation studies during the last years on FCC-ee [25-29] build upon the first parametric studies shown in [22-24, 30], which explored self-consistent monochromatization parameters [31], derived using the Guinea-Pig simulation tool [15]. Using these optimized parameters as a foundation, the first comprehensive optics design has been completed for FCC-ee GHC V22 [28,29]. The present work is taking these last studies as a basis and update for FCC-ee V23, making use of the new simulation tools currently being developed as Xsuite, among others.

FCC-ee GHC MONOCHROM IR DESIGN V23

The baseline FCC-ee lattice design, so-called "Global Hybrid Correction" (GHC) optics, has been developed for the Z and ttbar operation modes [32, 33]. These lattices are being updated regularly in order to implement the new requirements. In this framework, a monochromatization IR optics designs have been successfully implemented for GHC V22 in the Z and ttbar operation kind of optics at 62.5 GeV [28,29]. The studies presented here for the updated Z-mode lattice in V23 follow a similar methodology to that of [25-29] for V22. We focus specifically on the V23-based design, with key parameters of the monochromatization optics summarised in Table 1, alongside those of the scaled energy 62.5 GeV standard optics for comparison.

IP Horizontal Dispersion Generation (ZH mode)

To meet the requirements of transverse monochromatization, a non-zero horizontal dispersion (~1cm) must be introduced at the IP. Within the baseline GHC FCC-ee V23

* Corresponding author: anna.korsun@ijclab.in2p3.fr
† now at Synchrotron SOLEIL, Gif-sur-Yvette, France

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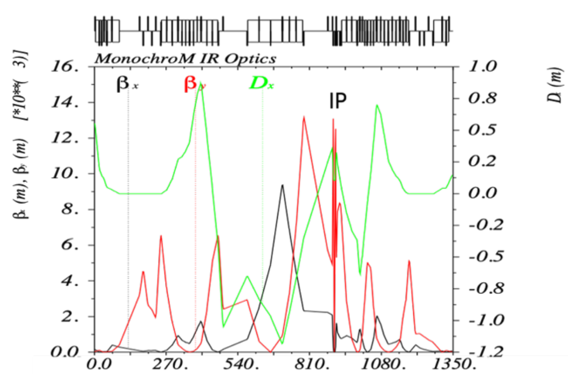
IR layout, this is achieved by optimizing the dipole angles distribution of the Local Chromatic Correction (LCC) system of the Final Focus System (FFS) by grouping them in a chicane configuration [31]. In this configuration the lengths and positions of initial dipoles relative to the initial trajectory (without IP dispersion) are not affected. These rearrangements introduce a controlled deviation in the beam orbit relative to the standard trajectory.

To increase flexibility in optics matching, all horizontal LCC dipoles in the IR are segmented into three slices, allowing thin quadrupoles to be inserted between them [26]. Through careful matching and optimization, four smoothly integrated chicanes are embedded within the LCC system. This design effectively generates the required horizontal dispersion at the IP while minimising the growth in horizontal emittance and with a minimal orbit change [27]. The optics are matched to reproduce the FCC-ee self-consistent monochromatization parameters, with a horizontal dispersion of 0.105 m at the IP [31]. Additionally, the beam parameters at the IR entrance and exit, as well as the phase advances of the IR sextupoles, are aligned with those of the standard Z-mode optics to ensure compatibility and integration into the global lattice. The result of monochromatization GHC V23 IR optics design using MAD-X [34] is presented in Fig. 1 (Top). Besides, Fig. 1 (Bottom) illustrates the comparison between the original standard IR orbit (grey) and the monochromatization orbit (red), with the point Z = 0 and X = 0 indicating the IP.



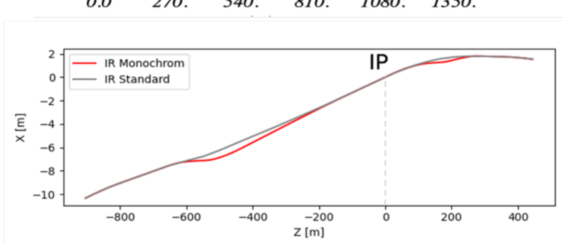


Figure 1: Top: FCC-ee MonochroM GHC V23 IR optics with non-zero horizontal IP dispersion. Bottom: FCC-ee standard IR orbit (grey line) and MonochroM IR orbit (red line). Both are calculated with MAD-X.

IP Vertical Dispersion Generation (ZV mode)

In the FCC-ee GHC lattice, the extremely low vertical emittance (~1 pm) results in a vertical beam size at the IP much smaller than the horizontal one. To achieve enough monochromatization factor, as defined in Eq. (1), an IP vertical dispersion of around mm is required, which is about 100 times smaller than one needed in the horizontal case. This small vertical dispersion is introduced by adjusting the strength of skew quadrupoles in the IR, which are also used to correct roll-induced vertical dispersion. These skew quadrupoles are positioned at the same locations as the sextupole pairs in the LCC system. This means that no change is needed either in dipoles or in the orbits. While maintaining zero vertical dispersion at the entrance and exit of the IR, the skew quadrupole strengths are tuned to produce 1 mm IP vertical dispersion. The resulting matched optics calculated in MAD-X is illustrated in Fig. 2.

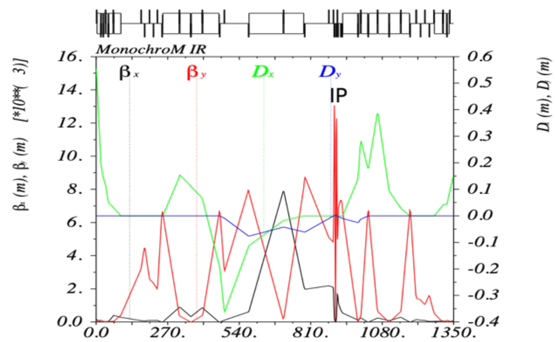


Figure 2: FCC-ee MonochroM GHC V23 IR optics with non-zero IP vertical dispersion (MAD-X).

MONOCHROM IR PERFORMANCE

Global implementation in GHC FCC-ee lattice

To evaluate the global performance of the two FCC-ee monochromatization IR optics designs presented in the previous section, each was individually implemented into the full ring by replacing the corresponding standard IR optics. Prior to performance evaluation, local and global chromaticities were corrected without changing the arc sextupoles, but only the LCC sextupoles. The machine tune was adjusted to the standard value, and synchrotron radiation (SR) losses were compensated by adjusting RF [29]. The non-optimized dynamic aperture (DA) plot, simulated with Xsuite, is presented in Fig. 3 A.

DA Optimization Studies

A global DA optimization algorithm has been recently implemented in the Xsuite code [35]. This algorithm is based on the rematching of the arc sextupoles. The global optimization consists of sequential steps. The first step is called DIRECT (Dividing RECTangle) and starts from chromaticity correction using auxiliary sextupole knobs. The method iteratively adjusts main sextupole parameters to maximize momentum acceptance, evaluated through particle tracking simulations in Xtrack. At each step, DIRECT performs a derivative-free global search over bounded parameter ranges to minimise particle loss based on survival metrics computed over many turns [36]. The first result of DIRECT DA optimization for GHC FCC-ee ZH V23 is presented in Fig. 3 B. Further optimization steps will be carried out in future studies.

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Table 1: Performance Parameters of GHC FCC-ee V23 MonochroM Optics

Parameters		**Standard* ZES V23**	**MonochroM ZH V23**	**MonochroM ZV V23**
# of IPs n_{IP}	[/]		4	
Circumference	[m]		90658.82	
Beam energy E_0	[GeV]	62.5	62.5	62.5
Energy loss/turn	[MeV]	138.2	143.	137.2
SR power loss	[MW]	49.7	50	49.3
Beam current I	[mA]	360	350	360
Bunches/beam n_b	[/]	12000	12000	12000
Bunch population N_b	[10^{11}]	0.57	0.55	0.57
Horizontal emittance ε_x (SR/BS)	[nm]	1.32/1.32	1.68/4.12	1.32 /1.32
Vertical emittance ε_y (SR/BS)	[pm]	2.64/2.64	3.33/3.34	4.2/534
Momentum compaction factor α_c	[10^{-6}]	28	27.4	27.9
$\beta^*_{x/y}$	[mm]	110/0.7	110/0.7	110/0.7
$D^*_{x/y}$	[m]	0/0	0.105/0	0/0.001
Energy spread σ_δ (SR/BS)	[%]	0.05/0.074	0.05/0.05	0.05/0.07
Bunch length σ_z (SR/BS)	[mm]	5.4/7.3	5.3/5.3	5.4/6.8
Synchrotron tune Q_s	[/]	0.041	0.041	0.041
Longitudinal damping time	[turns]	452	437	456
CM energy spread σ_W (with crab cavity)	[MeV]	64.9	27.17	46.9
Luminosity/IP (with crab cavity)	[10^{34}cm^{-2}s^{-1}]	18	9.35	0.95

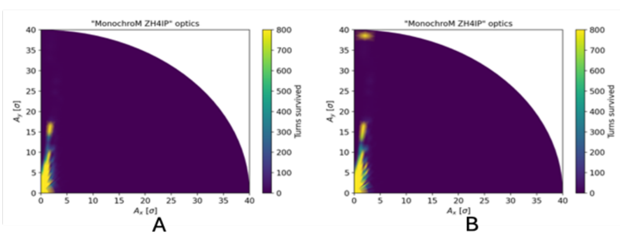

Figure 3: Simulated DA by Xsuite before optimization (A) and after DIRECT optimization (B) for GHC FCC-ee ZH V23.

Luminosity and CM energy spread

Luminosity and CM energy spread were calculated, using MAD-X and a semi-analytical approach [21] to take into account the BS, by means of Guinea-Pig code as in [25-30]. The results are provided in Table 1. For reference, the first column of Table 1 lists the beam parameters of the standard FCC-ee Z-mode optics scaled to 62.5 GeV (ZES V23). The subsequent columns present results for the two monochromatization optics: with IP horizontal/vertical dispersion (ZH V23/ZV V23), respectively, with a 4-IP configuration. The two monochromatization optics significantly reduce the CM energy spread compared to the scaled Z-mode optics at 62.5 GeV. So far, the configuration with horizontal IP dispersion offers higher luminosity and a better reduction in CM energy spread due to BS mitigation. The vertical dispersion scheme (ZV V23) could be further improved by optimizing the β_x^* to achieve a better CM energy spread reduction, as introduced for example in [29].

* No realistic implementation, only energy scale

SUMMARY AND OUTLOOK

Two IR optics have been developed for GHC FCC-ee V23, and an initial DA optimization has been carried out. The next steps include further DA optimization and beam-beam studies for the case of IP horizontal dispersion. In the case of the IP vertical dispersion, the β_x^* must be improved to mitigate the BS. Further goals include optimizing the optics to enhance luminosity, exploring a mixed monochromatization scheme combining horizontal and vertical dispersion, improving the CM energy spread of ZV4IP following the approach in [37]. The studies will also be dedicated to the GHC FCC-ee ttbar lattice.

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