# TOWARDS A MONOCHROMATIZATION SCHEME FOR DIRECT HIGGS PRODUCTION AT FCC-ee*

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*Abstract*

Direct Higgs production in $e^+e^-$ collisions at the FCC is of interest if the centre-of-mass energy spread can be reduced by at least an order of magnitude. A monochromatization scheme, to accomplish this, can be realized with horizontal dispersion of opposite sign for the two colliding beams at the interaction point (IP). We recall historical approaches to monochromatization, then derive a set of IP parameters which would provide the required performance in FCC $e^+e^-$ collisions at 62.5 GeV beam energy, compare these with the baseline optics parameters at neighbouring energies (45.6 and 80 GeV), comment on the effect of beamstrahlung, and indicate the modifications of the FCC-ee final-focus optics needed to obtain the required parameters.

## INTRODUCTION

Monochromatization is a proposed means of increasing the energy resolution of physics experiments at an $e^+e^-$ collider [1]. The monochromatization scheme increases the resolution in the centre-of-mass energies $\sigma_\omega$ for $e^+e^-$ interaction without reducing the inherent energy spread $\sigma_\epsilon$ of the colliding beams. To achieve this, opposite correlations between spatial position and energy are introduced in the colliding beams. In beam-optics terms, this requires, for example, a non-zero dispersion function of opposite signs for the two beams, at the interaction point (IP), to be generated by means of a special optical arrangement. Monochromatization has often been considered [1, 2, 3, 4, 5, 6, 7], but until now it has never been used, or tested, in any operating collider.

Monochromatization could enable an interesting option presently under study for the FCC-ee collider [8, 9], namely the possibility of direct Higgs production in the $s$ channel, $e^+e^- \to H$, at a beam energy of 62.5 GeV. This could result in an acceptable Higgs event rate, exactly on the Higgs resonance, and also provide the energy precision required to measure the width of the Higgs particle.

The FCC-ee collider consists of two horizontally separated rings for electrons and positrons. Therefore, dispersion at the interaction point (IP) can be generated independently for the two beams. In particular, horizontal dispersion at the IP could be generated with opposite signs.

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In the following we examine the impact of monochromatization on luminosity and measures to maximize the latter.

## MONOCHROMATIZATION PRINCIPLE

For a standard collision the relative spread in the centre-of-mass energy, $W = 2E_b$, is $\sqrt{2}$ times lower than the rms relative spread $\sigma_\delta \equiv \sigma_{E_b}/E_b$ in the beam energy $E_b$, namely

$$\left(\frac{\sigma_w}{W}\right)_{\text{standard}} = \frac{\sigma_\delta}{\sqrt{2}} \; . \qquad (1)$$

In a monochromatic collision we introduce IP dispersion of opposite sign for the two beams, so that particles with energy $E + \Delta E$ collide on average with particles of energy $E - \Delta E$ and the spread in the center of mass energy is reduced by the monochromatization (m.c.) factor $\lambda$,

$$\left(\frac{\sigma_w}{W}\right)_{\text{m.c.}} = \frac{\sigma_\delta}{\sqrt{2}}\frac{1}{\lambda} \; , \qquad (2)$$

with the monochromatization factor, for a horizontal IP dispersion $D_x^* \neq 0$,

$$\lambda = \sqrt{\frac{{D_x^*}^2 \sigma_\delta^2}{\epsilon_x \beta_x^*} + 1} \; . \qquad (3)$$

## BASELINE MONOCHROMATIZATION

Table 1 shows baseline parameters for FCC-ee at beam energies of 45.6 GeV and 80 GeV [9], together with emerging parameter sets for 62.5 GeV in a traditional head-on collision scheme, as well as with standard or with an attempted pushed optimzied monochromatization.

Given the resonance width of the standard model Higgs of 4.2 MeV and the much larger natural rms energy spread of the electron and positron beams at 62.5 GeV of about $6 \times 10^{-4}$ (or $\sim 40$ MeV), the monochromatization factor should be large, of order 10, or

$$\frac{{D_x^*}^2}{\beta_x^*} \geq 100 \, \frac{\epsilon_x}{\sigma_\delta^2} \approx 0.05 \text{ m} \; , \qquad (4)$$

using the emittance and energy-spread values due to arc synchrotron radiation (suffix “SR”), from Table 1.

For example, with $\beta_x^* = 0.25$ m we require a dispersion $D_x^*$ of at least 11 cm, with $\beta_x^* = 0.5$ m one of 16 cm, and $\beta_x^* = 1$ m implies $D_x^* \geq 0.22$ m.

Assuming the latter, the second 62.5 GeV column of Table 1 presents parameters for a “baseline manochromatization”, obtained by setting the bunch charge and beta functions equal to their nominal values at 45.6 GeV, and including the effect of beamstrahlung [10].

## PUSHING MONOCHROMATIZATION

The smaller the horizontal beta function can be made, the smaller is the horizontal beam size, and the lower the luminosity loss compared with a zero-dispersion collision. We assume that the horizontal beta function can be reduced a factor 4 below the present baseline, down to 0.25 m, without an inacceptable reduction in dynamic aperture. In this case the resulting horizontal beam size for monochromatization with $\lambda = 10$, dominated by the dispersion, is still much larger than for the standard collision schemes, which should help constrain the effects of beamstrahlung [10].

Table 1: Example beam parameters for FCC-ee crab-waist (CW) collisions at the Z pole and at the WW threshold [9], and for operation on the Higgs resonance in simple head-on (h.-o.) collision, and baseline or pushed monochromatization (m.c.), always considering $n_{\mathrm{IP}} = 2$ identical IPs.

| $E_e$ [GeV] | 45.6 | 62.5 | 62.5 | 62.5 | 80 |
|---|---|---|---|---|---|
| scheme | CW | h.-o. | m.c. basel. | m.c. push'd | CW |
| $I_b$ [mA] | 1450 | 410 | 410 | 410 | 152 |
| $N_b$ [$10^{10}$] | 0.7 | 3.3 | 3.3 | 8.5 | 6.0 |
| $n_b$ | 91500 | 80960 | 25760 | 10000 | 5260 |
| $\beta_x^*$ [m] | 1 | 1.0 | 1.0 | 0.25 | 1 |
| $\beta_y^*$ [mm] | 2 | 2 | 2 | 1 | 2 |
| $D_x^*$ [m] | 0 | 0 | 0.22 | 0.11 | 0 |
| $\epsilon_{x,\mathrm{SR}}$ [nm] | 0.09 | 0.17 | 0.17 | 0.17 | 0.26 |
| $\epsilon_{x,\mathrm{tot}}$ [nm] | 0.09 | 0.17 | 0.21 | 4.16 | 0.26 |
| $\epsilon_{y,\mathrm{SR}}$ [pm] | 1 | 1 | 1 | 1 | 1 |
| $\sigma_{x,\mathrm{SR}}$ [$\mu$m] | 9.5 | 9.2 | 132 | 66 | 16 |
| $\sigma_{x,\mathrm{tot}}$ [$\mu$m] | 9.5 | 9.2 | 144 | 323 | 16 |
| $\sigma_y$ [nm] | 45 | 45 | 45 | 32 | 45 |
| $\sigma_{z,\mathrm{SR}}$ [mm] | 1.6 | 1.8 | 1.8 | 1.8 | 2.0 |
| $\sigma_{z,\mathrm{tot}}$ [mm] | 3.8 | 1.8 | 1.8 | 1.8 | 3.1 |
| $\sigma_{\delta,\mathrm{SR}}$ [%] | 0.04 | 0.06 | 0.06 | 0.06 | 0.07 |
| $\sigma_{\delta,\mathrm{tot}}$ [%] | 0.09 | 0.06 | 0.06 | 0.06 | 0.10 |
| $L$ [$10^{35}$ cm$^{-2}$s$^{-1}$] | 9.0 | 2.2 | 1.0 | 1.7 | 1.9 |
| $\theta_c$ [mrad] | 30 | 0 | 0 | 0 | 30 |
| $\xi_x$ | 0.05 | 0.12 | 0.01 | 0.00 | 0.07 |
| $\xi_y$ | 0.13 | 0.15 | 0.04 | 0.03 | 0.16 |
| c.m. spread $\sigma_w$ [MeV] | 58 | 53 | 5.8 | 23.1 | 113 |
| $\lambda$ | 58 | 88 | 9.2 | 2.3 | 113 |

Since we reduce the horizontal beta function by a factor $\lambda_\beta = 4$ the luminosity loss would be equal to $\lambda/\sqrt{\lambda_\beta} \sim 5$, if we kept the bunch charge constant. However, in an attempt to profit from the larger horizontal beam size we tentatively increase the bunch charge $N_b$ until, with the nominal emittance, we reach the same vertical beam-beam tune shift as for the other cases. To push further, we now decrease the vertical beta function from $\beta_y^* = 2$ mm to 1 mm; this smaller beta function corresponds to a more ambitious baseline scenario [9]. The resulting smaller vertical beam size should increase the luminosity, while also lowering the beam-beam tune shift.

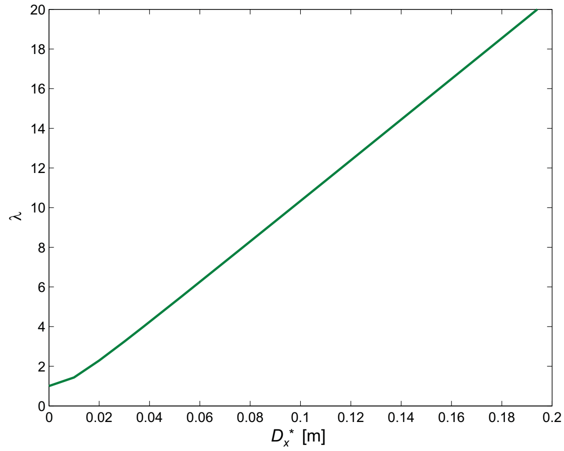


Figure 1: Monochromatization factor versus $D_x^*$ at fixed $\beta_x^* = 0.25$ m, for constant emittance and energy spread.

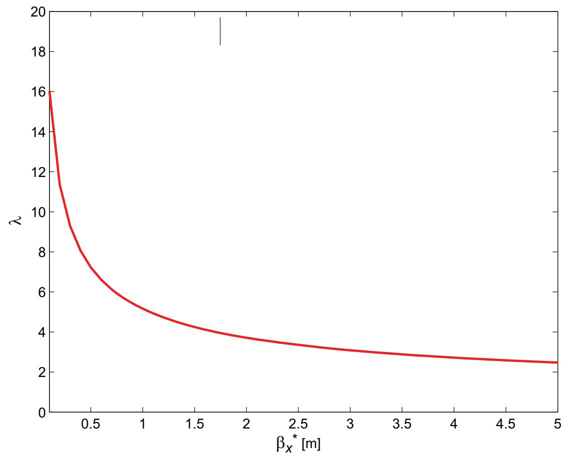


Figure 2: Monochromatization factor versus $\beta_x^*$ at fixed $D_x^* = 0.11$ m, for constant emittance and energy spread.

For operation on the Z pole and at the WW threshold FCC-ee applies a crab waist scheme with $\theta_c = 30$ mrad full horizontal crossig angle. The crossing angle also reduces the tune shift, especially in the horizontal plane. For our dispersion-based monochromatization scheme we may need to avoid the crossing angle and (effectively) operate with head-on collisions.

The beam-beam parameter is

$$\xi_{x,y} = \frac{\beta_{x,y}^* r_e N_b}{2\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)} \,. \tag{5}$$

With monochromatization this can be rewritten as

$$\xi_x \approx \frac{\beta_x^* r_e N_b}{2\pi\gamma\sigma_\delta^2 D_x^{*2}} \,, \quad \xi_y \approx \frac{\beta_y^* r_e N_b}{2\pi\gamma\sigma_\delta D_x^* \sigma_y^*} \tag{6}$$

For $D_x^* = 0.11$ m and other parameters (except for $N_b$) from Table 1, we find that a vertical beam-beam parameter of $\xi_y \approx 0.16$ (i.e. the same value as for the WW threshold)

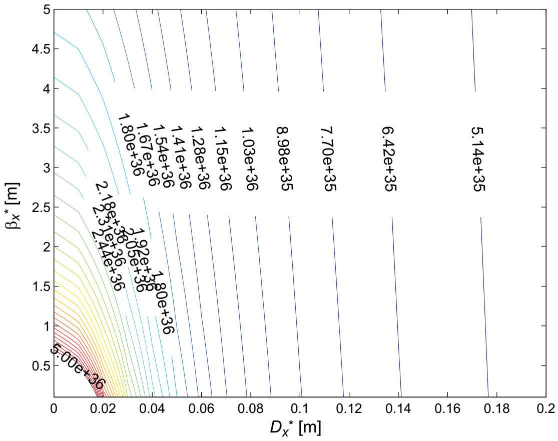


Figure 3: Luminosity as a function of $\beta_x^*$ and $D_x^*$, for constant emittance and bunch length.

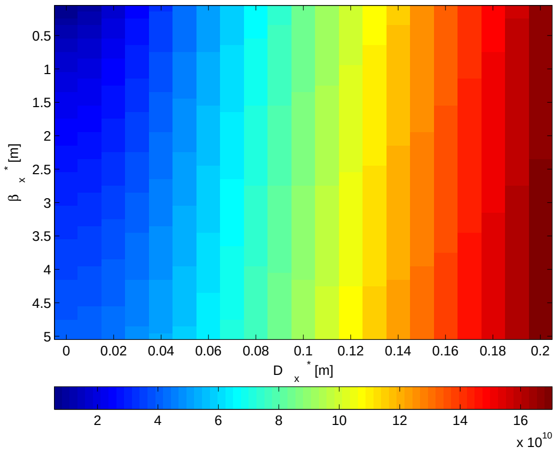


Figure 4: Bunch population as a function of $\beta_x^*$ and $D_x^*$ for constant emittance and bunch length.

is reached at a bunch population $N_b \approx 8.5 \times 10^{10}$. We adopt this value for our "pushed monochromatization".

Through the total current (limited by the synchrotron radiation power) the bunch population also defines the number of bunches per beam, $n_B$ and the overall luminosity $L$

$$L \approx \frac{f_{\rm rev} n_b N_b^2}{4\pi\sigma_y^* D_x^* \sigma_\delta} \approx \frac{I_b\gamma}{2er_e}\frac{\xi_y}{\beta_y^*} , \tag{7}$$

where $f_{\rm rev}$ denotes the revolution frequency (3 kHz).

Horizontal emittance and energy spread are normally determined by the optical lattice and the synchrotron radiation (SR) in the collider arcs. In the following figures we consider these two parameters as constant, equal to $\epsilon_{x,\rm SR}$ and $\sigma_{\delta,\rm SR}$, while we vary $D_x^*$ and $\beta_x^*$ through changes of the final-focus optics.

Figures 1 and 2 illustrate the dependence of the monochromatization factor on the horizontal beta function and on the IP dispersion, keeping the other parameters constant. Figures 3, 4 and 5 illustrate the variation of luminosity, bunch population, and energy spread in the $(\beta_x^*, D_x^*)$ plane, assuming the equilibrium emittances due to arc synchrotron radiation without any additional blow up caused

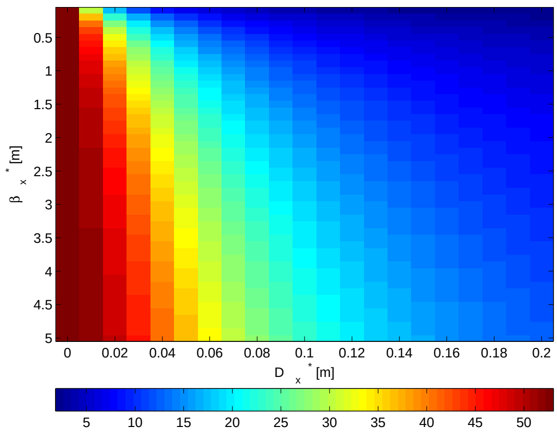


Figure 5: Centre-of-mass energy spread $\sigma_W$ in units of MeV as a function of $\beta_x^*$ and $D_x^*$ for constant emittance and bunch length.

by beamstrahlung [10] (i.e. suffix 'SR' in Table 1).

However, in the case of FCC-ee the transverse effect of beamstrahlung may not always be neglected. This can be seen in Table 1, which shows horizontal emittance and beam sizes first without and then including the effect of beamstrahlung [10]. For the pushed monochromatization scheme the beamstrahlung increases the horizontal emittance by more than a factor of 20! As a consequence the monochromatization factor $\lambda$ is reduced from a target value of 10 to about 2.3, which is not sufficient. The horizontal blow up was considered in the luminosity numbers of Table 1, but it was not taken into account in Figs. 1–5.

## CONCLUSION AND OUTLOOK

We have derived FCC-ee IP beam parameters which would result in about a factor 10 monochromatization at high luminosity. Accounting for the horizontal blow up due to beamstrahlung and nonzero IP dispersion, a luminosity of about $10^{35}$ cm$^{-2}$s$^{-1}$ can be reached on the Higgs resonance with an effective energy spread below 6 MeV. Further pushing the luminosity, through reduced $\beta_{x,y}^*$ and higher bunch charge, leads to large horizontal blow up and a concomitant degradation of the monochromatization.

The next challenge will be to modify the optics and layout of the FCC-ee final-focus system [11] so as to generate the desired antisymmetric IP dispersion, and, at the same time, transit from a crossing-angle to a head-on collision scheme. Either the additional bending magnets or electro-static separators needed to realize the head-on collision could be used to generate the needed IP dispersion, or we can maintain a crossing geometry and deploy crab cavities together with horizontal IP dispersion.

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