ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-TUP005

# STUDIES OF THE TRANSVERSE BEAM COUPLING IN THE EUROPEAN XFEL INJECTOR

M. Scholz*, B. Beutner, DESY, Hamburg, Germany

*Abstract*

Coupling between the transverse plains leads to an increase of the horizontal and vertical electron beam emittances. The coupling can be measured with dedicated multi quadrupole scans while the correlations of the beam are observed on a screen. In this paper we show the results from first coupling studies in the European XFEL injector.

## INTRODUCTION

SASE FELs like the European XFEL [1] depend strongly on the emittance, thus it is significant to investigate and optimize this parameter. Earlier multi quad scans revealed hints for transverse coupling of the electron beam thus we started further investigations. The technique how to measure the coupling between the transverse planes with multi quadrupole scans was e. g. demonstrated at the SwissFEL Injector Test Facility (SITF) [2]. This method was also used for the coupling measurements in the injector. Additional information can be found in [3]. In this paper, we present measurements of the transverse coupling in the European XFEL injector.

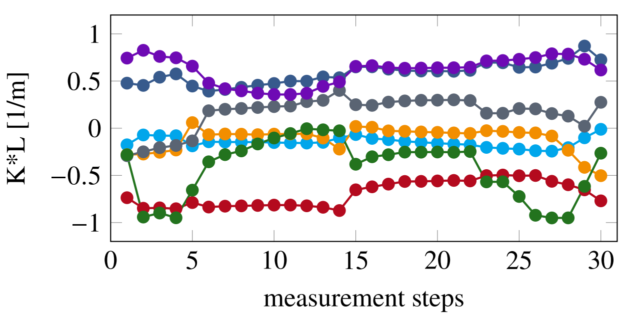


Figure 1: Normalized integrated strength of all quadrupole magnets used for the scan.

## EUROPEAN XFEL INJECTOR

A schematic layout of the European XFEL injector is presented in Fig. 4. Two superconducting accelerating modules are installed in the linac, a 1.3 GHz module and the third harmonic module, which operates with 3.9 GHz, to linearize the longitudinal phase space of the particle distributions. The design beam energy downstream these modules is 130 MeV. A subsequent diagnostic section including a transverse deflecting cavity as well as four screens [4] and a spectrometer allow to study the electron beam quality. All quads in the diagnostics section are equipped with individual bipolar power supplies.

* matthias.scholz@desy.de

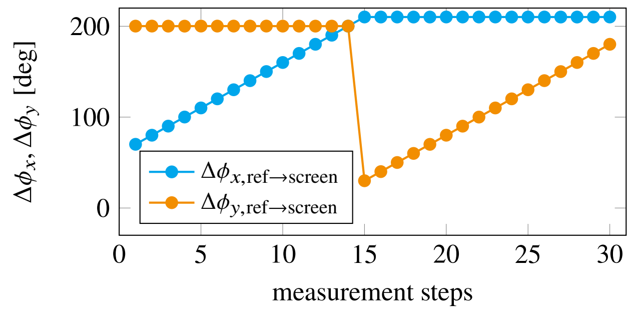


Figure 2: Phase advances in horizontal and vertical plane between optics reference position and the screen plotted for all scan steps.

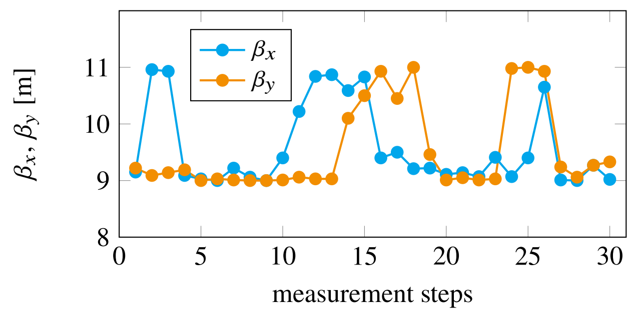


Figure 3: Horizontal and vertical beta functions at the screen for all steps of the phase scan.

## MULTI-QUADRUPOLE SCANS

The basic requirements on the quad scan for these measurements is to scan the phase advance between the optics reference position and the measurement screen in one plane over 180 degree (if possible) and keep it constant in the second one. Then the second plane has to be scanned while phase advance in the first plane is constant. In addition, the beam sizes should be kept preferably constant on the screen in order to ensure the same resolution for all measurement steps. A list with $k \times n$ entries of quadrupole strengths, fulfilling the described requirements mentioned above, has to be prepared. The number of measurement steps is $k$, here $k = 30$, and the number of quads is $n$, here $n = 7$. All $k$ quadrupole settings are then applied one by one to the machine. For each setting, the transverse particle distribution at the measurement screen is saved for evaluation. For the quad scan discussed in this paper, all 7 quadrupole magnets between the laser heater chicane and the last screen in the diagnostics section were used. Figure 1 shows the integrated strengths of all seven quads and for all 30 measurement steps. The phases advances of the quad scan are shown in Fig. 2.

ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-TUP005

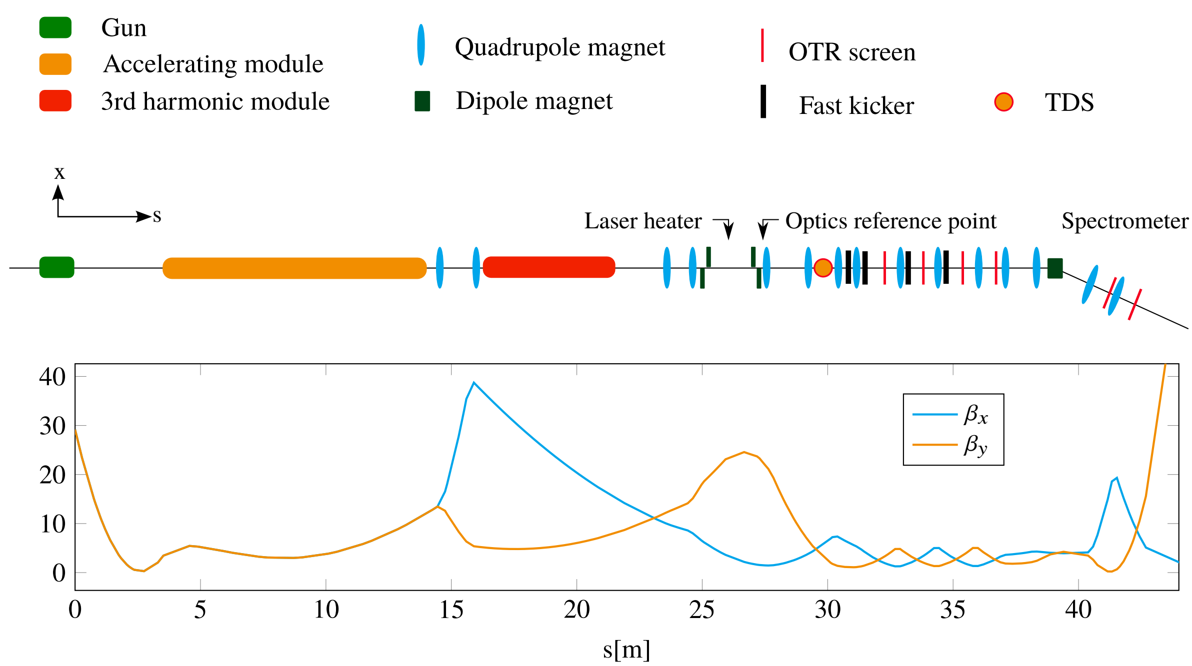


Figure 4: The default beta functions in the XFEL injector starting at the photo cathode and ending in the injector dump. Above the plot one can find a schematic layout of the XFEL injector. The last screen in the diagnostics section upstream the spectrometer dipole was the measurement position. All quadrupole magnets between the laser heater and the measurement screen were used for the scan of the phase advances.

It shows the data for both planes and for all 30 measurement steps. The large number of quads gives enough flexibility to keep the beta function on the screen almost constant during the scan as it is shown in Fig. 3.

## EVALUATION METHOD

The 4D beam matrix $\sigma^{4D}$ describes the full transverse distribution of the beam [2, 3]:

$$\sigma^{4D} = \begin{pmatrix} \langle x^2\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle \\ \langle xx'\rangle & \langle x'^2\rangle & \langle x'y\rangle & \langle x'y'\rangle \\ \langle xy\rangle & \langle x'y\rangle & \langle y^2\rangle & \langle yy'\rangle \\ \langle xy'\rangle & \langle x'y'\rangle & \langle yy'\rangle & \langle y'^2\rangle \end{pmatrix}. \quad (1)$$

The horizontal plane is described with $x$ and $x'$, the vertical plane respectively with $y$ and $y'$. All mixed matrix elements describe the transverse coupling of the beam.

The particle distribution at a position $s$ can be calculated from the starting distribution at position $s_0$ with the transport matrix $R_{s\rightarrow s_0}$,

$$\sigma_s^{4D} = R_{s\rightarrow s_0}\sigma_{s_0}^{4D} R_{s\rightarrow s_0}^T \quad (2)$$

Thus $\langle x^2\rangle_{k,s}$, $\langle y^2\rangle_{k,s}$ and $\langle xy\rangle_{k,s}$ can be described as follows:

$$\begin{aligned} \langle x^2\rangle_{k,s} =& R_{k,11}^2\langle x^2\rangle_{s_0} + R_{k,12}^2\langle x'^2\rangle_{s_0} + 2R_{11}^k R_{12}^k\langle xx'\rangle_{s_0} \\ \langle y^2\rangle_{k,s} =& R_{k,33}^2\langle y^2\rangle_{s_0} + R_{k,34}^2\langle y'^2\rangle_{s_0} + 2R_{33}^k R_{12}^k\langle yy'\rangle_{s_0} \\ \langle xy\rangle_{k,s} =& R_{k,11}R_{k,33}\langle xy\rangle_{s_0} + R_{k,12}R_{k,33}\langle x'y\rangle_{s_0} \\ &+ R_{k,11}R_{k,34}\langle xy'\rangle_{s_0} + R_{k,12}R_{k,34}\langle x'y'\rangle_{s_0} \end{aligned}$$

where $R_{k,ij}$ is the $ij$-element of the transfer matrix $R_{s\rightarrow s_0}$ for the $k^{\text{th}}$ measurement step.

The same parameters can be obtained from the measurements data as follows:

$$\langle uv\rangle_{k,s} = \frac{\sum v_i w_i q_{s,k,i}}{\sum q_{s,k,i}} \quad (3)$$

with $u$ and $v$ referring either to $x$ or $y$. The sum is taken over all pixels $i$ and $q_{s,k,i}$ is the intensity of the respective pixel as measured at the screen (position $s$ and measurement step $k$). A noise cut procedure [5] was used before the picture evaluation in order to reduce impact from beam halo. The beam moments at position $s_0$ can then be obtained fitting the data of the $k$=30 different measurements of the quad scan.

All scripts for these measurements and data reconstruction were tested with simulations. We were able to reconstruct the coupling terms from various simulated initial particle distributions using the same transfer matrices as for the quad scan in the injector.

## MEASUREMENTS AND EVALUATION

Quadrupole scans as described above were carried out with a beam of 500 pC bunch charge and 130 MeV beam energy. Ten data sets were taken for each setup. For each measurement step one exemplary beam spot taken on the screen is shown in Fig. 5. Figure 6 shows the horizontal and vertical beam sizes $(\langle x^2\rangle_{k,s})^{1/2}$ and $(\langle y^2\rangle_{k,s})^{1/2}$ as measured. The data shown in Fig. 7 shows the coupling term $\langle xy\rangle_{k,s}$ for each measurement step. All reconstructed parameters like

ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-TUP005

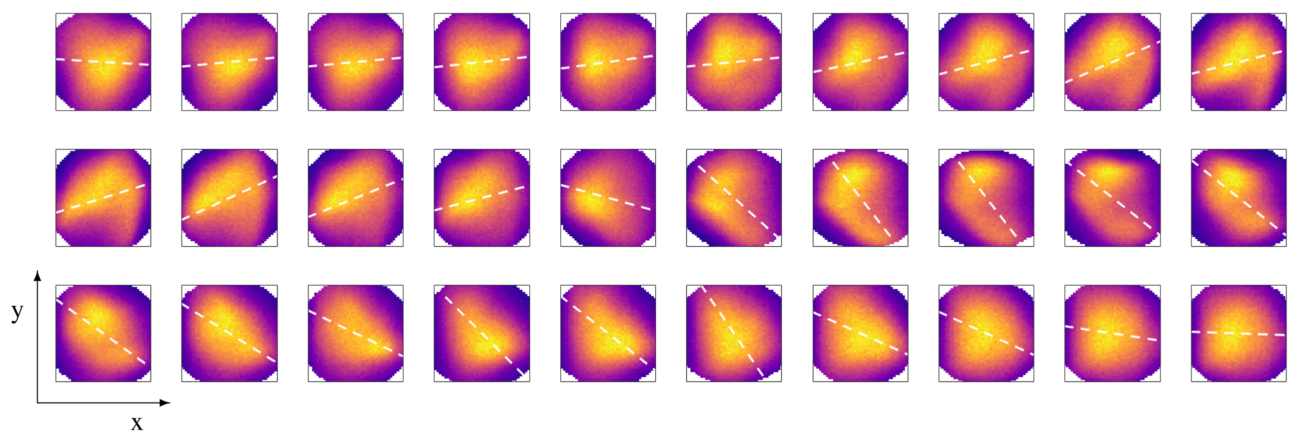


Figure 5: Beam spots on the screen for all 30 steps of the measurement. The first one in shown top left, the last one bottom right. The dashed lines shows the detected slope of the correlation between horizontal and vertical plain.

the emittances as well as the coupling parameters $\langle xy\rangle_{s_0}$, $\langle x'y\rangle_{s_0}$, $\langle xy'\rangle_{s_0}$ and $\langle x'y'\rangle_{s_0}$ can be found in Table 1.

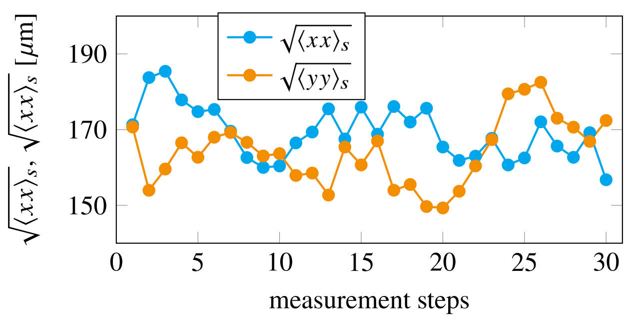


Figure 6: Horizontal and vertical beam sizes at the screen for all steps of the measurement.

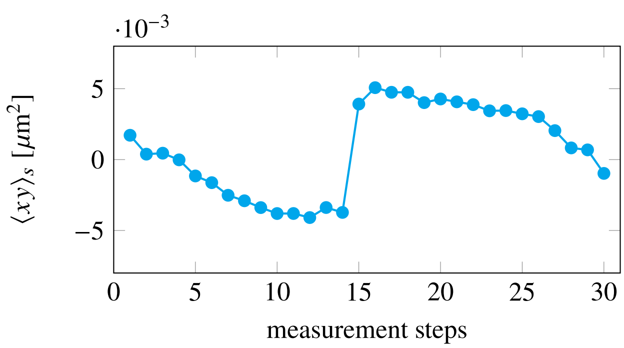


Figure 7: The coupling parameter $\langle xy\rangle_s$ for all measurement steps.

## CONCLUSIONS

We established a method to measure the transverse beam coupling between $x$ and $y$ plane for the injector of the European XFEL. First measurements and evaluations could be carried out. Recently installed quadrupole and skew-quadrupole magnets on the main solenoid of the electron gun can be used to change the transverse coupling of the beam [6]. Future measurement can then be used to minimize those effects.

Table 1: Reconstructed Parameters

| | | |
|---|---|---|
| $\epsilon_x$ | = | 0.77 mm mrad |
| $\epsilon_y$ | = | 0.71 mm mrad |
| $\langle xy\rangle_{s_0}$ | = | $51.14 \cdot 10^{-9}$ m$^2$ |
| $\langle x'y\rangle_{s_0}$ | = | $-52.26 \cdot 10^{-9}$ m |
| $\langle xy'\rangle_{s_0}$ | = | $-11.57 \cdot 10^{-9}$ m |
| $\langle x'y'\rangle_{s_0}$ | = | $11.51 \cdot 10^{-9}$ |

## ACKNOWLEDGMENT

We like to thank all colleagues who have been involved in the construction, building and commissioning of the European XFEL.

## REFERENCES

[1] M. Altarelli *et al.*, "The European X-Ray Free-Electron Laser, Technical design report", DESY 2006-097 July 2007.

[2] E. Prat and M. Aiba, "Four-dimensional transverse beam matrix measurement using the multiple-quadrupole scan technique", *Physical Review Special Topics - Accelerators and Beams* 17, 052801, 2014.

[3] F. Löhl, "Measurement of the transverse emittance at the VUV-FEL", *TESLA-FEL* 2005-03, 2005.

[4] Ch. Wiebers *et al.*, "Scintillating screen monitors for the transverse electron beam profile diagnostics at the European XFEL", WEPF03, in *Proceedings of IBIC'13*, Oxford, UK, 2013.

[5] B. Beutner and E. Prat, "Considerations about optics-based phase-space measurements at linac-based FEL facilities", in *Proceedings of FEL'11*, TUPA18, 2011.

[6] M. Krasilnikov *et al.*, "Electron beam asymmetry compensation with gun quadrupoles at PITZ", presented at FEL'17, WEP007, 2017.