DESY Summer Student Program 2009

Correction of the electron beam trajectory to displace the undulator axis at FLASH

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Abstract

Due to beam line misalignments, the longitudinal axis of the radiation created in the FLASH undulators may sometimes not be created with the photon beam line. A simulation program has been developed to calculate the necessary shift of the quadrupoles to change the longitudinal axis of the undulator section. This program also corrects the beam trajectory on the new axis. The method used and the results are described in this program.

Contents

1 Introduction

DESY is one of the largest scientific research centres in the World. The main part is located in Hamburg, Germany. One of the leading topics of interests is the synchrotron radiation which is provided by FLASH – the prototype of the future international projects XFEL and ILC.

1.1 Motivation

The main aim of these studies has been to find a method of controlling the particle beam along the beam line sectors. This can be done by an application of the quadrupole offsets as well as setting the appropriate corrector currents.

The longitudinal axis of the beam line is defined by the centre (in the *xy*-plane) of the quadrupoles. Due to the beam line misalignments, the longitudinal axis of the radiation may sometimes not be centred with the photon beam line. In that case, the undulator beam line can be adjusted by changing the position of individual quadrupoles which are equipped with micromovers.

1.2 FLASH

FLASH name stands for ***F**ree **E**lectron **LAS**er in **H**amburg*. The main goal for FLASH facility [3] is to provide SASE (Self-Amplified Spontaneous Emission) free electron laser radiation with a wavelength in the VUV range down to few nanometers (soft X rays).

Fig 1.1 shows an overview of FLASH facility and its most important parameters are shown in Tab.1.

In the photo-injector the electrons are produced in bunches and are accelerated in the superconducting RF cavities which operate at temperature of 2 K. At the energies of 127 and 450 MeV the electron bunch is longitudinally compressed. Finally, the particle beam reaches a 30 m long undulator – a periodic magnetic multipole structure, where photons are spontaneously emitted and interfere constructively. The self - amplified spontaneous emission

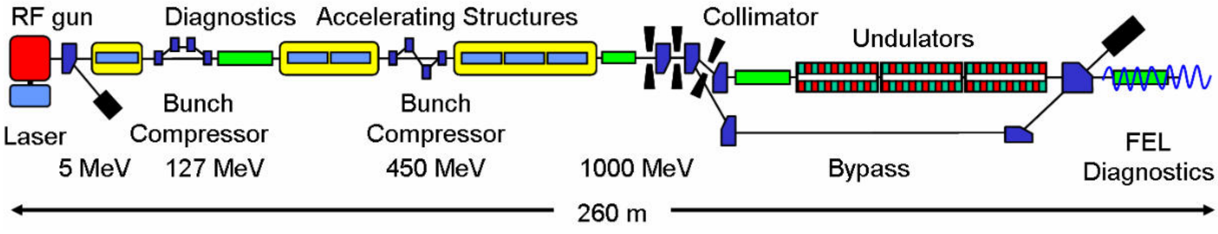

Fig. 1.1: Main components of the FLASH beam line (not to scale).

Tab.1: The main parameters of the FLASH facility.

Type of FEL amplification	SASE
Beam energy	Up to 1 GeV
Bunch charge	1nC
Normalized transverse emittance	< 2μm
Max. peak current (inside the bunch)	1-2 kA
Material type (undulators)	NdFeB
Peak magnetic field (undulators)	0.47 T
Min. achieved wavelength	6.5 nm
Pulse duration	5-50 fs
Peak brilliance	$\sim 10^{29}$

begins. Afterwards the electron beam is not used any longer, therefore a dipole magnet deflects it to the beam dump. In the meantime, the free electron laser radiation heads towards the experimental hall where can be used for three dimensional, time resolved observations and other physical processes. These investigations help in gaining the better understanding of the structure of matter.

Because FLASH is based on the principle of SASE radiation, an accurate beam steering through undulators is required. The electron beam overlaps with the laser beam only under certain desired circumstances which must be provided by the magnet alignment. Hence the particle beam trajectory axis and the beam line in the sector of undulators should be defined by the same straight line. This is equivalent with a situation when initial conditions (a position x and an angle x') of the electrons are consistent with relevant locations of magnets.

1.3 Transverse beam dynamics

In the linear approximation, the particle motion can be described using the transformation matrices [1]. For this reason the accelerator is divided into sectors with uniform properties. That gives a possibility of the particle trajectory reconstruction along the beam line.

Assuming that the strength of magnet $k\left[\frac{1}{m^2}\right]$ is constant along the longitudinal axis z, one can reduce the equation of motion to this of the harmonic oscillator:

$$u'' + ku = 0\,, \tag{1}$$

where u may stand either for x or y.

The solution of the equation (1) can be presented in the matrix formulation by:

$$\begin{pmatrix} u(z) \\ u'(z) \end{pmatrix} = \begin{pmatrix} C(z) & S(z) \\ C'(z) & S'(z) \end{pmatrix} \begin{pmatrix} u_0 \\ u'_0 \end{pmatrix} \tag{2}$$

where u_0 and u'_0 are arbitrary initial parameters of the particle trajectory, z is the independent variable of longitudinal position of the beam.

The matrix elements are described by cosine and sine like solutions:

$$C(z) = \cos(\sqrt{k}z) \text{ and } S(z) = \frac{1}{\sqrt{k}}\sin(\sqrt{k}z) \tag{3}$$

when $k>0$ and

$$C(z) = \cosh(\sqrt{|k|}z) \text{ and } S(z) = \frac{1}{\sqrt{|k|}}\sinh(\sqrt{|k|}z) \tag{4}$$

when $k<0$.

1.3.1 Drift space

Drift space is a region of accelerator where no forces act on the particle beam – neither bending nor focusing/defocusing effects occur. It is a magnet-free region therefore

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix}, \tag{5}$$

where x_0 and x'_0 are correspondingly initial position and initial angle of the beam while x and x' are the ultimate variables. Variable L stands for the straight length of that sector.

1.3.2 Corrector dipoles

When a charged particle moves in a magnetic field $\vec{B}$ [T] it experiences the Lorentz force

$$\vec{F} = q(\vec{v} \times \vec{B}) \tag{6}$$

$\vec{F}$ [N] is the bending force which acts on the particle moving with the velocity $\vec{v}\left[\frac{m}{s}\right]$, q is the charge and for electron beam becomes $q = e = 1.602 \cdot 10^{-19}$ [C].

A corrector dipole is built of two poles and its main task is to change the direction of the beam motion. In the simulations the following equations have been implemented:

$$x = x_0 + x'_0 \cdot L + \frac{1}{2}\frac{L^2}{r} \tag{7}$$

$$x' = x'_0 + \frac{L}{r} \tag{8}$$

The value L stands for the length of the corrector and r is a radius of the bending trajectory:

$$r = \frac{E}{B \cdot ce} \tag{9}$$

B is the magnetic field in the gap of the corrector and c is the speed of light.

1.3.3 Quadrupole

A quadrupole is a magnetic structure formed by four poles. Depending on the polarization of poles and the sign of the beam charge, the quadrupole can have either focusing or defocusing properties in one plane and the opposite in the other plane. The stability of the beam is achieved with sets of quadrupoles with alternating polarisations which are located one after the other (so-called FODO lattice).

The k-value determines the strength of magnets. If $k=|k_0|$ is positive, the quadrupole has the focusing properties, otherwise defocusing ones.

$$k = e \cdot \frac{g}{p} = \frac{c \cdot e \cdot g}{c \cdot p} = c \cdot e \cdot \frac{g}{E}, \tag{10}$$

where g – quadrupole gradient, E – beam energy.

An introduction of quadrupole phase (variable l is a path/arc length of an element)

$$\varphi = \sqrt{|k_0|}\,l \tag{11}$$

leads to the transformation matrices given by the following dependencies:

a) Focusing quadrupole ($k = |k_0| > 0$)

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cos\varphi & \frac{1}{\sqrt{k_0}}\sin\varphi \\ -\sqrt{k_0}\sin\varphi & \cos\varphi \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} \tag{12}$$

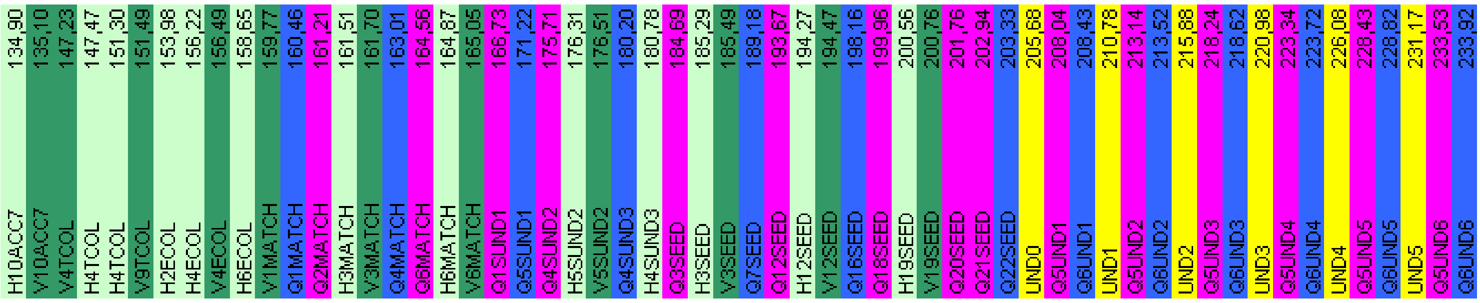

Fig. 3.1: Layout of FLASH. The abbreviations stand for*: H – corrector for horizontal plane, V – corrector for vertical plane, Q – quadrupole, UND – undulator. Drift spaces are omitted.*

b) Defocusing quadrupole ($k = -|k_0| < 0$)

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cosh\varphi & \frac{1}{\sqrt{|k_0|}}\sinh\varphi \\ \sqrt{|k_0|}\sinh\varphi & \cosh\varphi \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} \tag{13}$$

1.3.4 Undulator

Undulator is an insertion device composed of the periodic structures of dipoles with alternating directions of the magnetic field. In the horizontal plane the beam follows a sinusoidal trajectory while in the vertical plane it experiences a focusing effect which is described by the focal length *f*:

$$\frac{1}{f} = \frac{\lambda_u}{8r^2} \tag{14}$$

where λ_u is a period length. Then the transport matrixes are presented as follows:

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} 1 & \frac{1}{2}\lambda_u \\ -\frac{2}{f} & 1 \end{pmatrix} \cdot \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} \tag{15}$$

The value *r* is a radius of the trajectory when the magnetic field reaches the maximal value.

2 Trajectory simulations. Beam corrections in the horizontal plane

The trajectory of the beam through the undulators has been simulated using a program written in JAVA.

In the simulations only the final part of the FLASH beam line (Fig.1.1) has been implemented (Fig.3.1). That region begins with the corrector just downstream of the accelerator module ACC6 and ends with the quadrupole located at the end of the last undulator. The focusing and defocusing quadrupoles (correspondingly magenta and blue bars), correctors (green bars) and undulators (yellow bars) have been taken into account. A drift space has been located between distinguished parts of the layout. In the upper part of the picture, the positions of elements in respect to the location of RF gun (the first element in the beam line) are given.

The most crucial aspect of ensuring the SASE conditions is to keep all (or most of) the quadrupoles in the undulator section in the straight line.

In the simulations one quadrupole has been chosen as a constraint. This means that its offset is equal zero. Other quadrupoles have been adjusted to obtain the horizontal beam trajectory deviation of 1 mm on the Ce:YAG screen located at 254.45 m (Fig.3.2).

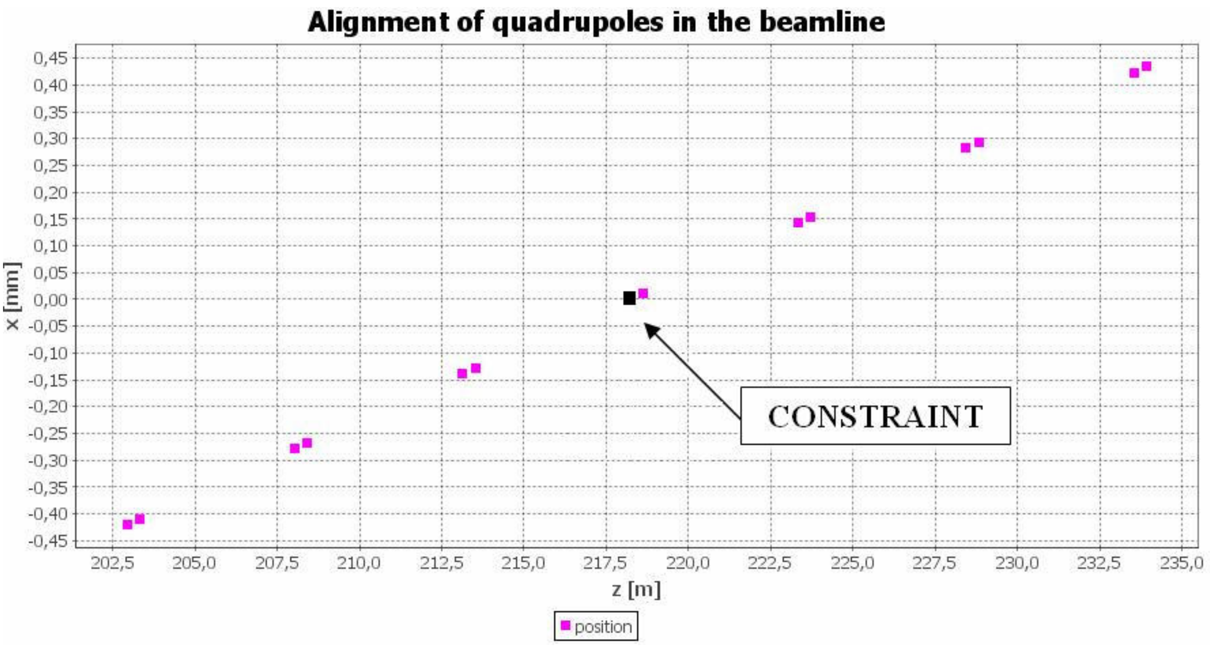

Fig.3.2: Quadrupole offset.

The simulated beam trajectory for the beam line with undulator quadrupoles shifted is shown in Fig.3.3. With this trajectory the beam does not overlap the photon beam and the SASE process does not take place. To this trajectory a correction has been applied to get the beam on the new axis. The electron beam has had the following initial conditions: a position in the horizontal plane: x_0 = 0 mm, an angle x'_0 = 0 rad. The applied beam energy has been 1GeV.

The correction of the beam trajectory can be performed in two independent ways. The first scenario has assumed the application of only two correctors (while all other correctors have been turned off).

The particle beam motion is described by the linear superposition of applied corrector currents. Therefore the set of equations can be written as follows:

$$x_i I_i + x_j I_j = V \tag{16}$$

$$x'_i I_i + x'_j I_j = \alpha \tag{17}$$

Indexes i and j refer to the first and second correctors chosen. The foregoing notation denotes that the individual corrector current I_i has been applied. From the beam trajectory the elements x_i and x'_i at the constrained quadrupole have been derived. The same procedure has been proceeded for the second corrector j. These variables contribute to the final state $\begin{pmatrix} V \\ \alpha \end{pmatrix}$, where V is a position and α is an angle of the particle beam at the beginning of the undulator sector. They are dependent on the initial conditions of the beam (x_0, x'_0 and the energy E).

After simple calculations one obtains the solution for I_i and I_j :

$$I_j = \frac{\alpha \cdot x_i - x'_i V}{x'_j x_i - x_j x'_i} \tag{18}$$

$$I_i = \frac{V - x_j I_j}{x_i} \tag{19}$$

The corrector currents have had to be set with these values to provide SASE requirements. Fig. 3.4 presents results for two chosen correctors: H12SEED and H19SEED. The calculated values are -0.0211 A and -0.0019 A correspondingly. The constraint has been given by the Q5UND3 quadrupole.

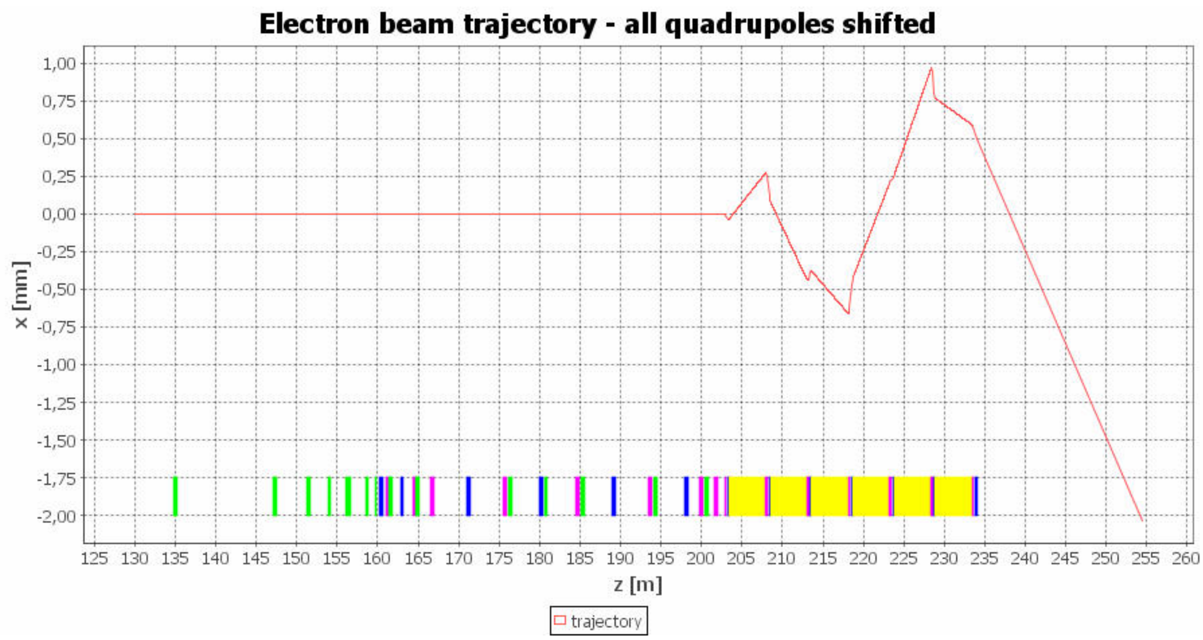

Fig.3.3: All quadrupoles have been shifted by the values shown on Fig.3.2.

The other way of manipulating the beam trajectory is an application of only one corrector (while all others are switched off) and a shift of the first (Q21SEED) quadrupole in the region of undulators. Then the corrector current gives a kick to the particle beam and aligns it with a proper position and an angle. In this case the constraint can be only applied on the second quadrupole in the line (Q22SEED).

The corrector current has been set on -9.276e-4 A and the quadrupole has been shifted within 8.332e-2 mm in the horizontal plane. The results are presented on the Fig.3.5.

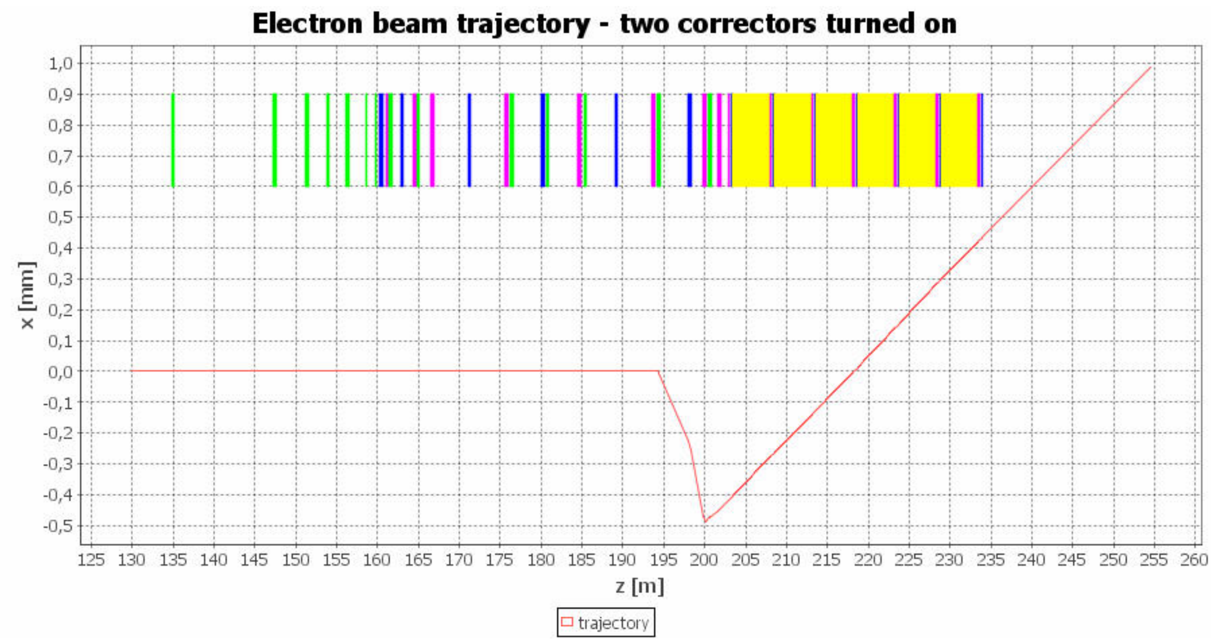

Fig.3.4: The electron beam trajectory in the case of use two correctors.

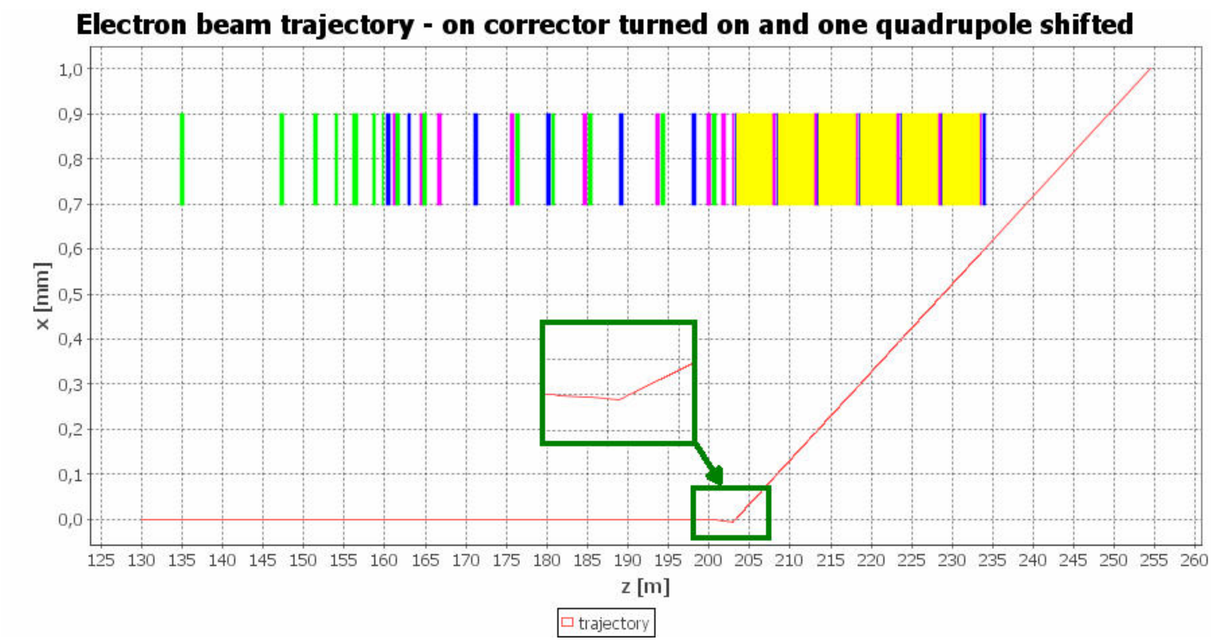

Fig.3.5: Application of one corrector and the shift of one quadrupole.

3 Conclusions

The studies on FLASH electron beam have been performed in JAVA programming language. Simulations contain deliberations of the beam control and steering in the horizontal plane. Although only the final part of the real FLASH layout has been considered, the new elements can be introduced easily.

The user of the program can choose two correctors and the constrained magnet as well as one corrector and the first quadrupole shift to obtain the beam distortion with the desired angle. The output is presented by 2D plot of the beam motions and the values of corrector currents and quadrupole offsets, which need to be applied, are given.

4 Outlook

The same procedure, as shown above, can be applied in the vertical plane. However, due to the focusing effects of undulators the motion of electrons in the vertical plane makes the change of the axis more sophisticated. The focusing effect of the undulators has been integrated in the simulation program. The impact of the undulator focusing the beam trajectory is shown in Fig. 3.6.

In that case all correctors as well as all quadrupoles have been switched off (currents equal zero) and no offset has been applied (the angle equals zero). Only the initial position *y* of electron been has been set to 1 mm (*y'* = 0 rad).

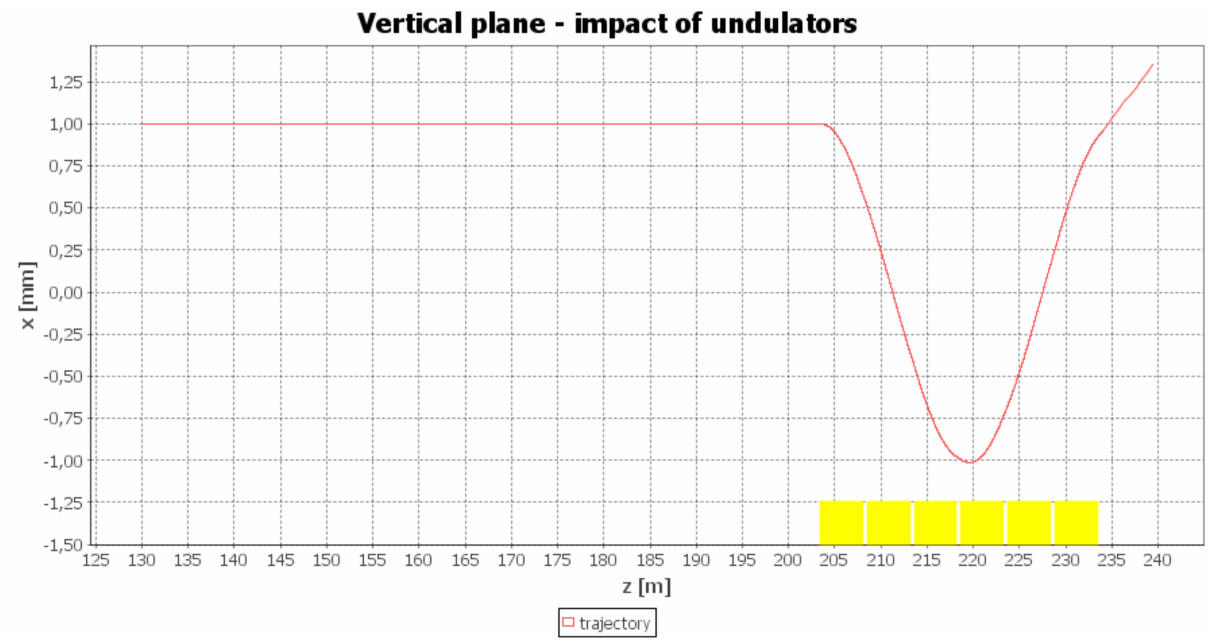

Fig.3.6: *Focusing influence of undulators in vertical plane. Beam energy 0.5 GeV.*

5 Acknowledgments

First of all, I would like to thank my supervisor, Dr Pedro Castro, for the interesting topic of investigations and significant remarks while writing this report.

I'm also really grateful to Mr Joahim Meyer and Mrs Andrea Schrader for great organisation of DESY Summer Student Program 2009, scientific tours and mesmerising lectures! Thanks a lot!

Special thanks go to my officemate, Martin Nuss, for enriching my JAVA programming skills and help in finding bugs in the code ;-)

6 Abbreviations

FLASH	*Free Electron LASer in Hamburg*
FEL	*Free Electron Laser*
ILC	International Linear Collider
RF	Radio Frequency
SASE	Self-Amplified Spontaneous (Stimulated) Emission
VUV	Vacuum Ultra Violet
XFEL	X-ray Free Electron Laser

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8 Bibliography

[1] "*Particle Accelerator Physics*" H.Wiedemann, Springer Third Edition 2007

[2] "*Accelerator Physics and Engineering*", A. Wu Chao, M.Tigner, World Scientific 2nd Printing 2002

[3] http://flash.desy.de/