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Beam trajectory investigations with degaussed quadrupoles in the undulator section in FLASH

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Abstract

A straight beam trajectory along the undulator section is mandatory for a high-gain FEL. Therefore, the tolerances for fabrication errors of undulator magnets are very tight. For FLASH [1], the second field integral along the beam axis of a 4.5-meter undulator segment should not exceed 30 T.mm^2, which represents a beam trajectory offset of 10 μm at 1 GeV at the exit of the undulator segment. Six undulator segments have been installed so far in FLASH that have values for the second field integral below 10 T.mm^2 as measured in the lab stand [2]. However, the horizontal beam position has to be corrected inside the undulator section in order to get a straight trajectory through the undulator section. In a dedicated beam experiment, where the quadrupole magnets inside the undulator section have been degaussed, the integrated corrector dipole field applied is 0.41 T.mm per undulator segment. The method applied to determine this correction strength is presented.

1 Introduction

The undulator section in FLASH [3] consists of six undulator segments, each with a length of 4.5 m. Pair of quadrupoles are located between undulator segments as well as upstream and downstream the undulator system. These quadrupoles are needed to increase the electron density and thus to increase the FEL gain. It is however possible to change the optics [4] in order to transport the beam along the undulator section (with a vacuum chamber of 9 mm diameter) with these quadrupole pairs off. Additional to their DC power supplies, these quadrupoles are connected via relays to a AC power supply used as degausser. For beam diagnostics purposes, there is a horizontal and a vertical wirescanner [5] between each pair of quadrupoles.

Each undulator segment is equipped with a 0.9 m long correction coil that introduces a dipole field in the vertical direction. The design goal for these steerers is to separate horizontally the electron beam from the photon beam in order to stop the FEL process and measure the FEL output power after an effective shorter undulator. In this experiment we have used these steerers to get the beam through the undulator section with quadrupoles off.

2 Description of the experiment

The goal of this experiment is to measure the strength of the horizontal deflection acting on the beam along the undulator section. Therefore, we remove (or minimize) any source of steering (either due to an beam offset at a quadrupole field or due to dipole fields) along the 50 m of beam line between quadrupole Q12SEED located at 193.67 m (10 m upstream the first undulator segment) and quadrupole Q9EXP located at 242.92 m (9 m downstream the last undulator segment), with the exception of the steerers located inside the undulator segments. At the same time, we minimize the beam position down to less than ±0.1 mm at BPM (Beam Position Monitor) 12SEED located inside quadrupole Q12SEED and at BPM 9EXP located inside quadrupole Q9EXP. The magnet layout in this area is shown in Fig. 1.

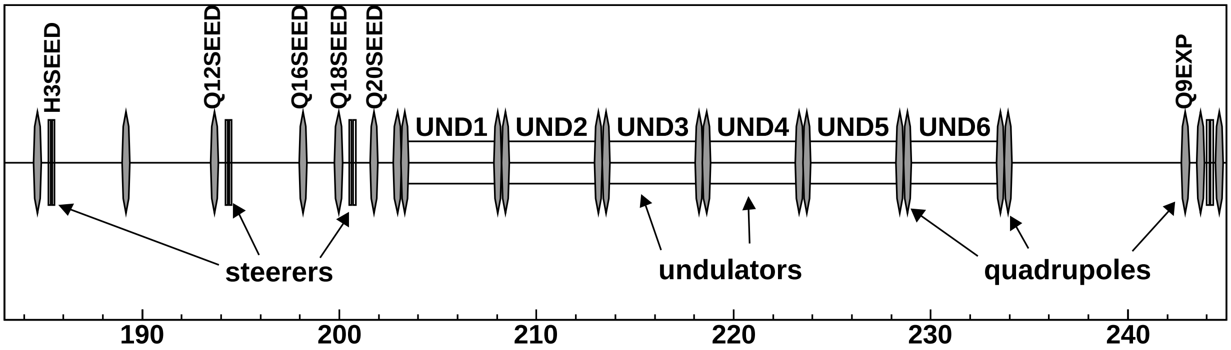

Figure 1: Magnet layout in the area around the undulator section in FLASH (the steerers inside undulator segments are not shown). The electron beam enters from the left side. The horizontal scale is in meters. Some of the names assigned to the components in FLASH are indicated. Quadrupole names begin with 'Q' and horizontal steerer names begin with 'H'.

The experiment was carried out in four steps:

1. matching the optics after degaussing the quadrupoles in the undulator section.
2. removing the dipole fields in steerer magnets located upstream the undulator up to steerer H3SEED (located at 185.3 m).
3. minimizing the beam offset at quadrupoles located upstream the undulator up to quadrupole Q16SEED (located at 198.16 m).
4. adjusting the strength of the undulator steerers to get a minimum beam offset at the BPM 9EXP (located 9 m downstream the last undulator segment).

Steps 2 and 3 are for minimizing the incoming beam angle at the entrance of the undulator and are described in Sec. 3. Step 4 is explained in detail in Sec. 4.

3 Minimizing the horizontal incoming angle into the undulator

With undulator quadrupoles off, a non-zero angle of the beam trajectory at the entrance of the undulator will introduce a position offset along the undulator section and downstream. Of course, such horizontal incoming angle can be corrected with the steerer located in the first undulator segment. This correction introduces a (undesirable) systematic error in the measurement of the horizontal beam deflection along the undulator that must be avoided.

In order to minimize the beam trajectory angle at the entrance of the undulator, it is required to align precisely the beam trajectory upstream the undulator section. To do so, we have first degaussed all horizontal steerers located up to 20 m upstream the undulator (including steerer H3SEED located at 185.29 m). Then, we have minimized the beam position measured by BPMs located up to 20 m upstream the undulator (including BPM 3SEED located at 184.69 m). At the same time, we have minimized the beam offset at three quadrupoles upstream the undulator located at 198.16 m (Q16SEED), at 199.96 m (Q18SEED) and at 201.7 m (Q20SEED), which are 5.2 m, 3.4 m and 1.7 m from the entrance of the undulator, respectively. With these settings, the measured beam position (averaged over 100 bunches) is 0.040 ± 0.003 mm at BPM 3SEED and is -0.082 ± 0.003 mm at BPM 12SEED (located at 193.67 m).

In order to determine the center of the quadrupoles, we have changed one by one their strength and have observed their steering effects at BPMs located downstream. Then, we have changed the incoming beam trajectory (using steerers located at 176.3 m and upstream) in order to move the beam position closer to the center of these three quadrupoles simultaneously. Afterwards, we have measured once again the steering effects of each quadrupole. Analysing this and the previous steering results, we have estimated the final relative position of the beam with respect to the center of each quadrupole. The results from this quadrupole beam-based alignment are summarized in Tab. 1 together with the corresponding quadrupole beam deflection.

quadrupole	Δx **[mm]**	g **[T/m]**	α **[μrad]**
Q16SEED	-0.1	-1.3	16
Q18SEED	-0.2	1.2	-28
Q20SEED	0.1	-0.7	-8

Table 1: Relative offsets between beam and quadrupole center determined with beam-based alignment and their corresponding beam deflection for $E = 0.68$ GeV. The resulting beam deflection RMS is 19 μrad.

A beam offset Δx from the center of a quadrupole field with gradient g introduces a beam deflection given in thin lens approximation by

$$\alpha = c\, e\, \frac{g\, L_{eff}}{E}\, \Delta x \tag{1}$$

where E is the beam energy, L_{eff} is the effective quadrupole length, c is the light velocity in vacuum and e is the electron charge.

After minimizing the horizontal incoming angle with this procedure, we estimate that the residual angle at the entrance of the undulator is ≤ 20 μrad.

4 Minimizing the horizontal angle at the exit of the undulator

Starting with the basic approach that the beam deflection is uniformly distributed along the undulator section, we have powered all six steerers in the undulator segments with the same current. Having all quadrupoles off until BPM 9EXP (located 10 m downstream the last undulator segment), we find a minimum offset at this BPM for a current of -3.6 A applied to all undulator steerers. With these settings the horizontal beam profiles have been measured with wirescanners. The horizontal beam position along the undulator recorded with wirescanners is shown in Fig. 2 and compared with the beam position recorded with a steerer current of -3.7 A (dashed line). The horizontal beam position at BPM 9EXP (located at 242.93 m) is 0.35 mm for -3.7 A. Thus, the accuracy in the determination of the steering needed to minimize the exit angle is estimated to be around 1%.

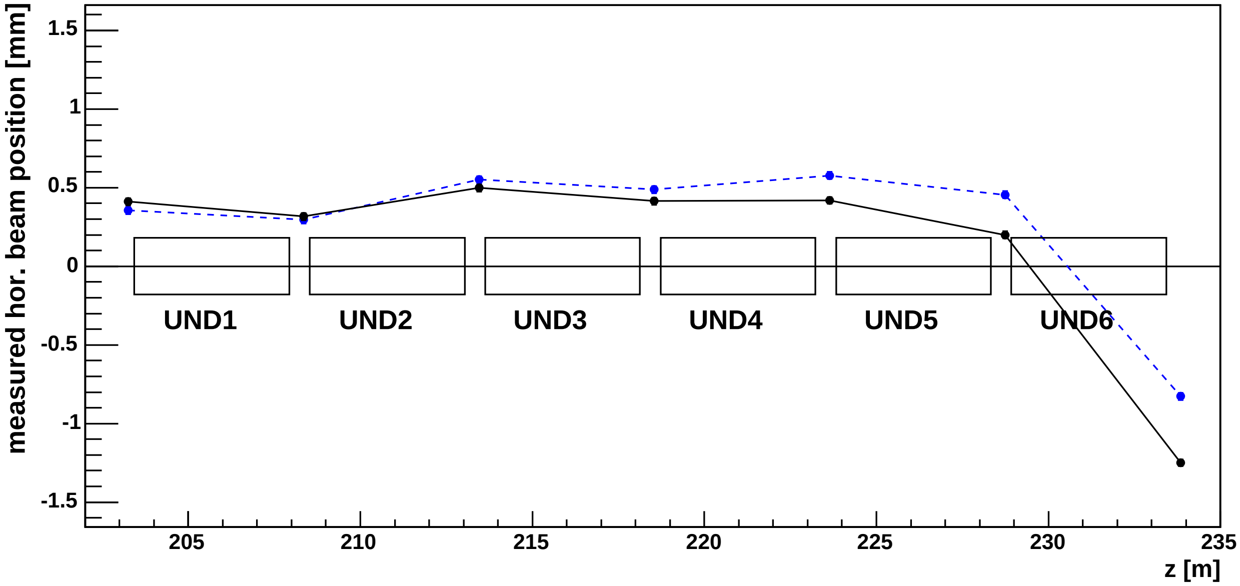

Figure 2: Measured horizontal beam position with wirescanners in undulator section with all undulator steerers set to -3.6 A (full line) and to -3.7 A (dashed line). The electron beam enters from the left side.

The beam trajectory measured with wirescanners (shown in Fig. 2) is parallel to the undulator axis. Excluding the last wirescanner located at 233.84 m, the trajectory angle is within ± 5 μrad. In both cases (with currents -3.6 A and -3.7 A), the beam position measured with wirescanners (excluding the last one) is 0.4 mm in average with a standard deviation of 0.1 mm, which indicates a good relative alignment between wirescanners. Since no additional steering is applied at the entrance of the undulator section, we conclude that the beam incoming angle is sufficiently minimized with the procedure described in Sec. 3. Moreover, this result confirms that the assumption of a uniform distributed dipole field along the undulator section is in first order correct.

The beam position measured with the wirescanner located just downstream the last undulator segment has an offset of about -1.6 mm with respect to the other measured positions. If the assumption of a uniform beam deflection along the undulator is correct, then we conclude that the wirescanner itself has an offset with respect to the others. If we assume on the contrary that the last wirescanner is physically well aligned with respect to the others, we can try to correct the beam position at the exit of the undulator with steerers in the undulator section. In order to do that, we select the steerer in undulator 5 and change its current by 3 A. The beam position measured after this change is shown in Fig. 3 compared with the previous measurements. The measured beam position with the last wirescanner is now comparable with the other wirescanners. However, the beam position downstream the undulator has an offset about 2 mm, which means that the beam angle at the exit of the undulator is large. Based on that, the most likely explanation is that the last wirescanner has a horizontal offset with respect to the other wirescanners.

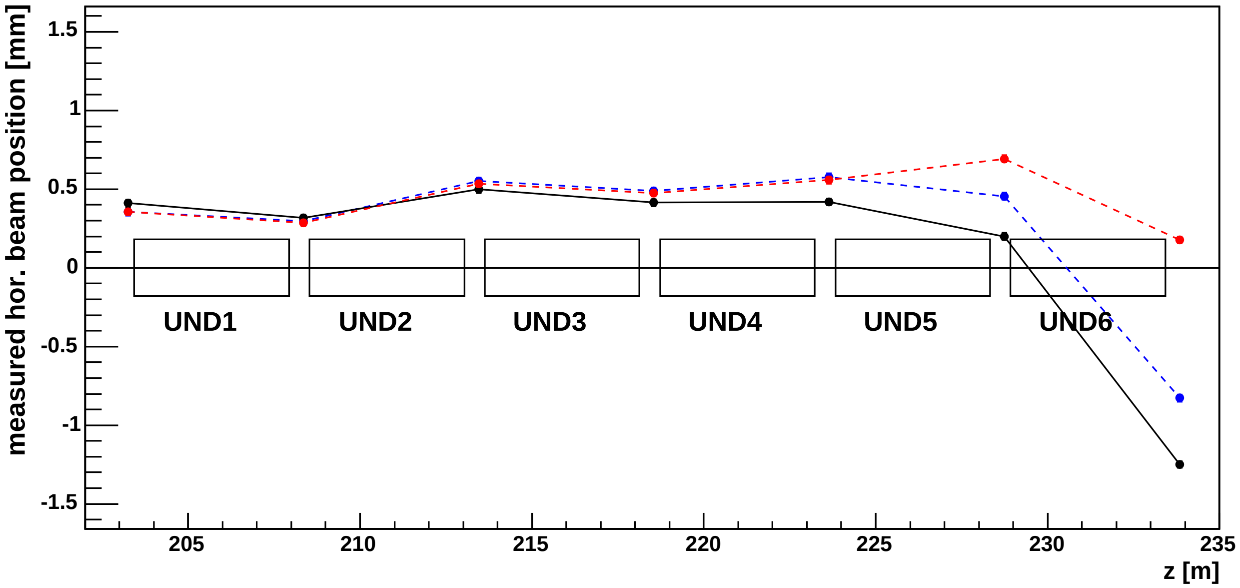

Figure 3: Same measurements as in Fig. 2 with an additional measured horizontal beam position with all undulator steerers set to -3.7 A, except the steerer in undulator 5 which is set to -6.7 A.

5 Measurement of the undulator steerer strength

The strength of the steerer installed in the undulator segment has been measured using difference beam position measurements. We have changed the current of the steerer located in the first undulator segment by 1 A and recorded the change of the beam trajectory using horizontal wirescanners. The horizontal beam position change measured with all seven wirescanners is shown in Fig. 4. A linear fit to the four data points from the wirescanners just downstream the steerer yields a beam angle change of -50 ± 1 μrad. The corresponding dipole field change of the steerer can be calculated using

$$\alpha = c \cdot e \cdot \frac{\int Bdl}{E} \tag{2}$$

where B is the magnetic dipole field. The result is an integrated dipole field of 0.113 ± 0.002 T.mm/A which is in agreement with the value of 0.114 T.mm/A calculated using a magnetic model [6]. Based on this result, we calculate the corrector strength applied per undulator segment for a steerer current of -3.6 A to be 0.41 T.mm.

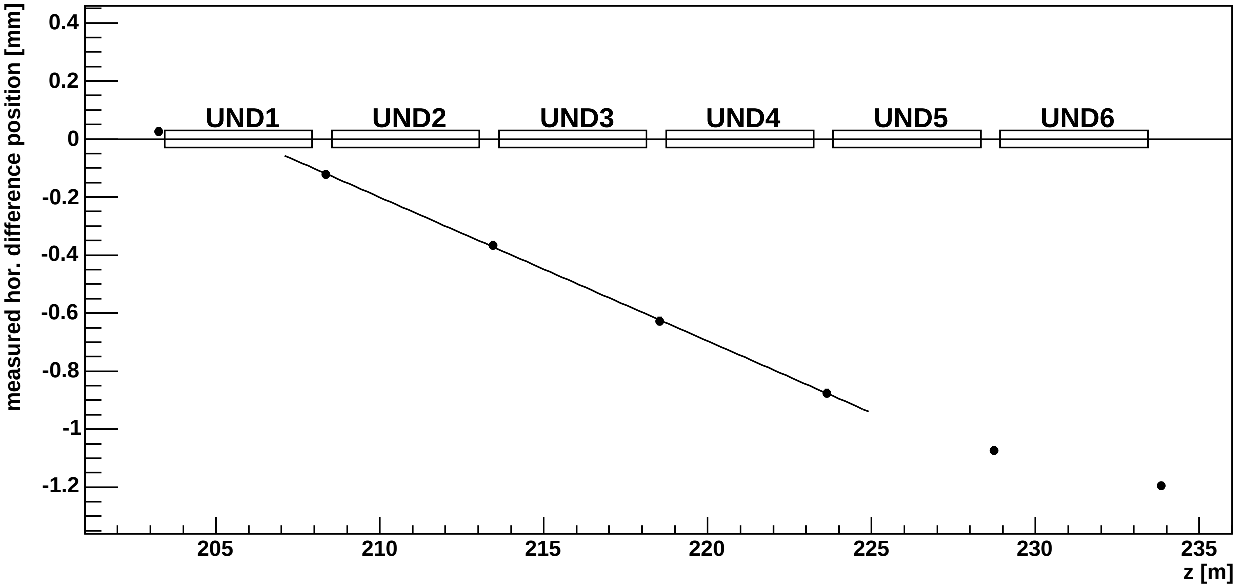

Figure 4: Difference beam position measured with wirescanners for a current change of 1 A in the steerer located in the first undulator segment UND1.

6 Beam trajectory simulations in the undulator section

With undulator quadrupoles off, the undulator section is, in principle, a drift space in the horizontal plane. In this case, the dipole fields of undulator steerers set to a current of -3.6 A will deflect the trajectory of a 0.68 GeV beam by a total 1.08 mrad along the undulator section. A simulation of the beam trajectory along the undulator section is shown in Fig. 5, assuming that the beam is on axis at the entrance of the undulator section. In this case, the beam position has an offset of about 15 mm at the exit of the undulator. Such a beam trajectory is simply not possible, since the diameter of the vacuum chamber is 9 mm.

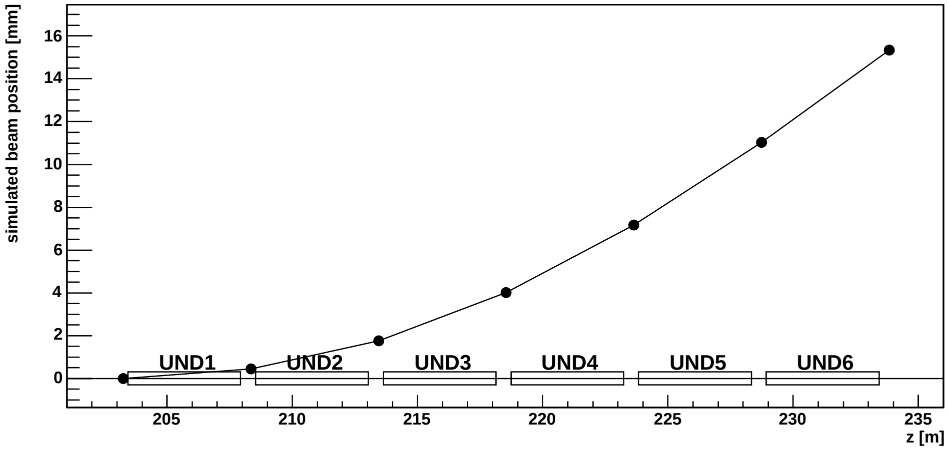

Figure 5: A simulation of the beam trajectory along the undulator section with the beam on axis at its entrance and assuming that the undulator steerers are the only dipole field (with all undulator quadrupoles off).

It is however possible to simulate a beam trajectory that fits inside the vacuum chamber of the undulator. An example of such beam trajectory is shown in Fig. 6, where a beam has an offset of 2 mm and an angle of 0.5 mrad at the entrance of the undulator. In this case, the beam offset never exceeds ±2 mm inside of the undulator section.

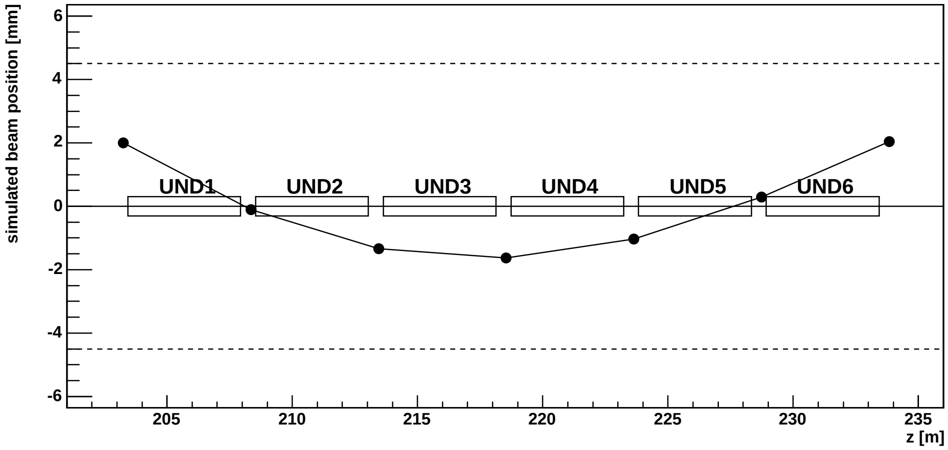

Figure 6: A simulation of the beam trajectory along the undulator section with a beam offset of 2 mm and angle of -0.5 mrad at the entrance and assuming that the undulator steerers are the only dipole field (with all undulator quadrupoles off). The two horizontal dashed lines mark the limits of the vacuum chamber.

Although this kind of trajectory is possible inside the undulator section, it is in contradiction with the measured beam trajectory shown in Fig. 2 and is in contradiction with the results of the minimization of the beam angle at the entrance and exit of the undulator. In fact, with steering-free quadrupoles Q16SEED, Q18SEED and Q20SEED (as described in Sec. 3), an incoming beam angle of 0.5 mrad would indicate that these quadrupoles have offsets of 4.5 mm, 3.6 mm and 2.8 mm, respectively, with respect to the accelerator axis. Furthermore, the beam position would have an offset of 7 mm at both BPMs 12SEED and 9EXP. This kind of trajectory would also imply that the wirescanners have different and large offsets (up to 2 mm) with respect to the undulator axis.

7 Conclusions

We present a method to measure the horizontal beam deflection in the undulator section. With this method, we have determined a beam deflection of 1.08 ± 0.02 mrad for a beam of 0.68 GeV (to the left in the direction of the beam) occurring along the undulator section. This deflection is (in first order) uniform and corresponds to a vertical magnetic field (pointing to the ceiling) with a integrated strength of 0.41 ± 0.01 T.mm per undulator segment. The reason for this deflection is not yet understood. In order to compensate this deflection, we have applied a current of -3.6 A to the steerers located inside the undulator segments. The resulting beam trajectory is parallel to the undulator axis and has a standard deviation of 0.1 mm measured by the wirescanners (excepting for the last wirescanner that presents an offset of approx. 1.5 mm). For this experiment all quadrupoles in the undulator section are degaussed and the beam angle is minimized at the entrance and at the exit of the undulator.

8 Acknowledgments

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