IS THERE A GOLD ORBIT AT FLASH?

Oleg Tatsyuk, (supervisor Pedro Castro-Garcia)

DESY, MPY Department

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Abstract

In this report we analyze data collected by Beam Position Monitors at FLASH from June 2010 to August 2011. We have selected measurements taken during the user runs when the photon intensity of the FEL is high. Then we have analyzed the transverse beam position along the undulators as a function of beam energy and measurement time. As a result of our analysis we can conclude that the best reference orbits ("golden" orbits) taken for high FEL photon intensities do not change significantly on the beam energy nor in time. Therefore, we have selected a central "golden" orbit and we show statistically that this orbit is a good reference orbit for FEL runs independent of beam energy, measurement time and bunch charge.

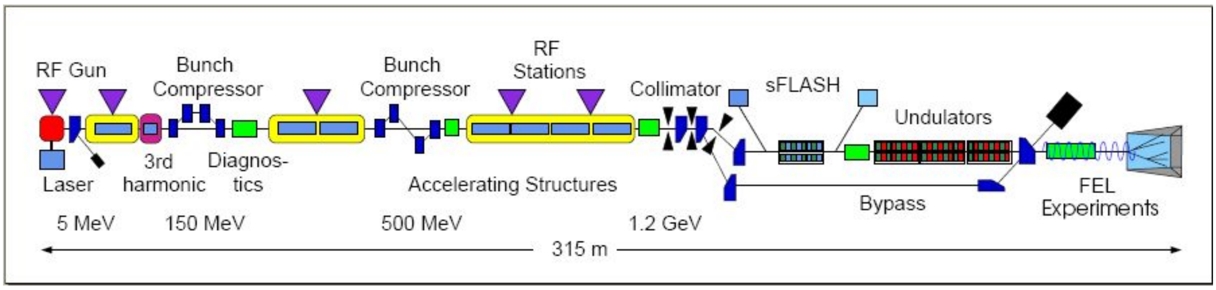
Introduction

FLASH was constructed to generate radiation in the vacuum ultraviolet and soft X-ray regions. To get high photon intensity (high-gain FEL) we need to have a good transverse overlap between the electron and the photon beam. So, we need to have a straight trajectory of electron bunches inside the undulators. For this reason the investigation of spatial characteristics of particle beam is very important.

Experimental setup

FLASH (Free Electron Laser in Hamburg) is a user facility for producing entirely coherent, bright and ultra-short pulses of extreme-ultraviolet radiation and soft X-rays in special undulators, as well as a test facility for the European XFEL (X-Ray Free Electron Laser) and the ILC (International Linear Collider).

Figure 1. The principal scheme of Free Electron Laser FLASH



The electron bunches are produced in a laser-driven photoinjector (RF Gun in the Fig. 1) with tiny emittances mandatory for an efficient self-amplified spontaneous emission process. At intermediate energies of 130 and 470 MeV the electron bunches are longitudinally compressed by magnetic Bunch Compressors, thereby increasing the peak current mandatory for producing femtosecond X-ray in the undulators. Seven superconducting accelerator modules allow to accelerate thousands of bunches per second to up to 1.2 GeV, before passing about 30 m of undulators. A collimator removes the beam halo which might cause radiation damage in the permanent magnets of the undulators. The 30 m long undulators consists of permanent magnets. The electrons interact with the undulator field in such a way, that so called micro bunches are developed. These micro bunches radiate coherently and produce intense X-ray pulses. Finally, a dipole magnet deflects the electron beam safely into a dump, while the FEL radiation propagates to the experimental hall.

Total length of FLASH accelerator is about 260 m. Undularors are settled at a distance of about 200 m to 230 m from RF gun.

For measuring the spatial characteristics ((x,y,z) coordinate) of particle beam about 60 Beam Position Monitors (BPMs) are installed along the accelerator.

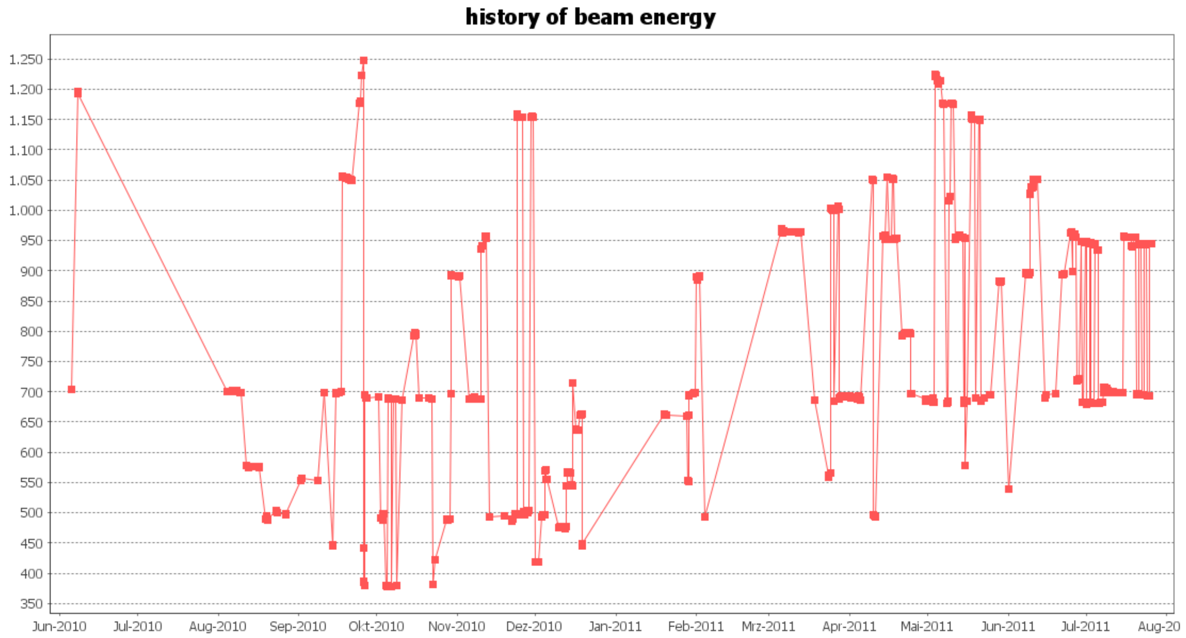
The data we analyze contains the position of particle beam, the value of electron bunch charge, beam energy, time of measurement and the intensity of photons emitted by electron bunches in the undulator magnetic field.

Method to analyze the orbit data at FLASH

Most FLASH accelerator experts say that an orbit of electron bunches when the FEL output is high with different parameters (beam energy, time measurement and so on) differs from each other. Another words, electron bunches with different energy or measurement time have different orbits and for each data selection (beam energy selection, time measurement selection) the so-called “golden” orbits are different. To see how much the golden orbit changes we have to choose data with one parameter selection and compare the average orbits.

We first select orbits measured when photon intensity is more than 50 μJ. Fig.2 shows the beam energy and the time when measurements were taken.

Figure 2. History of beam energy for 589 orbits taken with photon intensity > 50 μJ



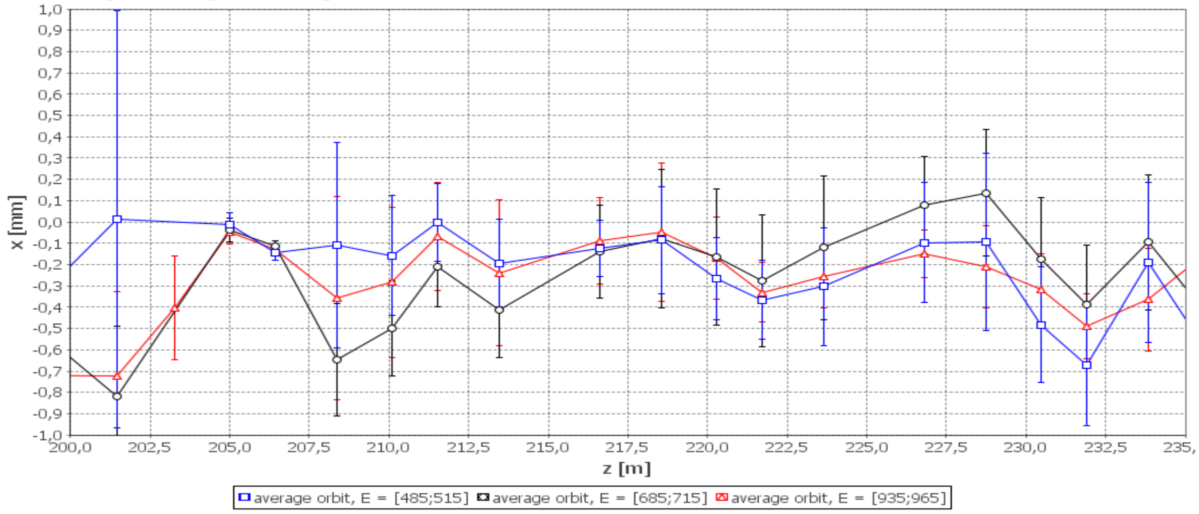
To see how much the golden orbit changes we choose data with beam energy range selection.

Beam energy range selection

Based on the history of beam energy shown in Fig.2 the following beam energy ranges have been selected: [485; 515] MeV, [685; 715] MeV, [935; 965] MeV.

The average orbits and standard deviation with the beam energy ranges pointed above and the difference between average orbits with E = [685; 715] MeV and E = [935; 965] MeV, and with E = [685; 715] MeV and E = [485; 515] MeV are shown in Fig.3 and Fig.4 accordingly.

Figure 3. The average orbits of measurements with the beam energy range [485;515] MeV; [685;715] MeV; [935;965] MeV



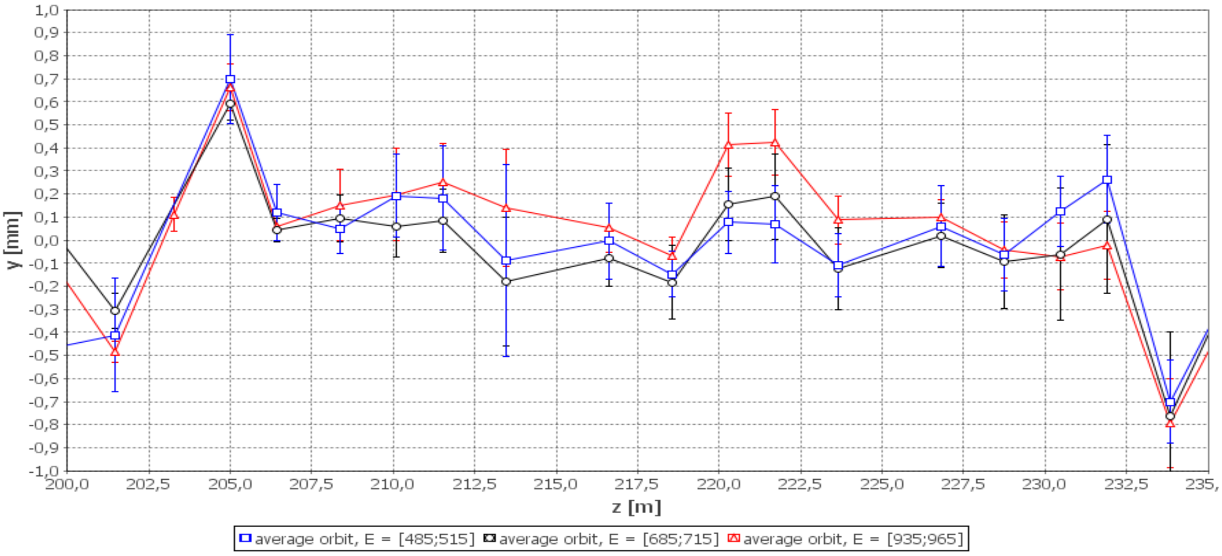
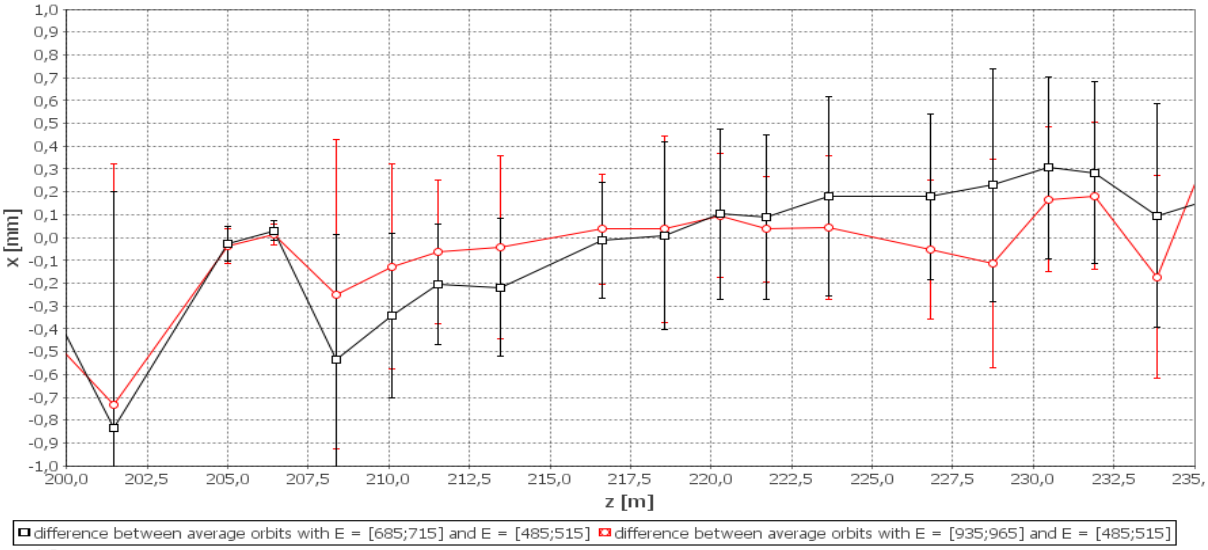


Figure 4. The difference between average orbits with E = [685;715] MeV; E = [935;965] MeV and average orbit with E = [485;515] MeV



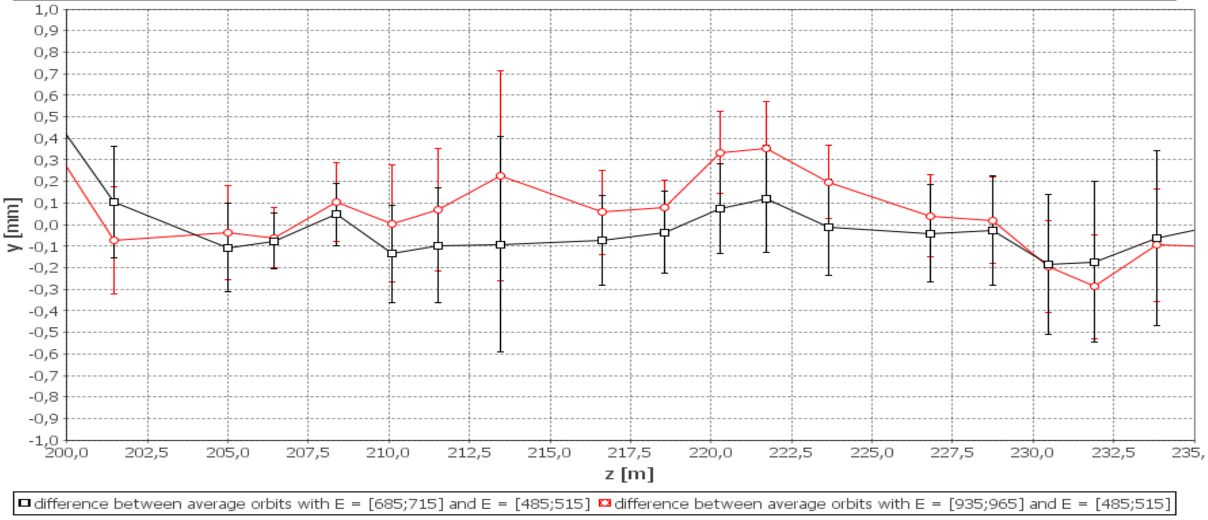


Fig.3;4 shows that taking into account standard deviation, the average orbits of electron bunches with different energy ranges are the same, therefore if the “golden” orbit exists it is unique one for all electron bunches with different beam energy selections.

Time period of measurements selection

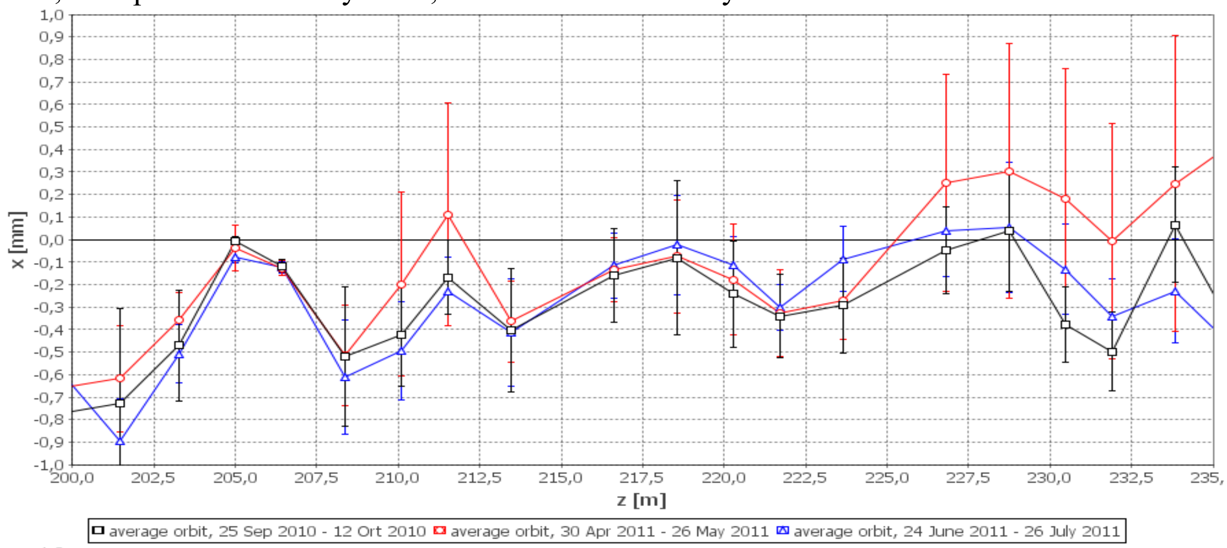
We select measurements taken within 3 time periods:

1 time period: 25 September 2010 – 12 October 2010

2 time period: 30 April 2011 – 26 May 2011

3 time period: 24 June 2011 – 26 July 2011

Figure 5. The average orbits of measurements with measurement time 25 Sep 2010 - 12 Oct 2010; 30 Apr 2011 - 26 May 2011; 24 June 2011 - 26 July 2011



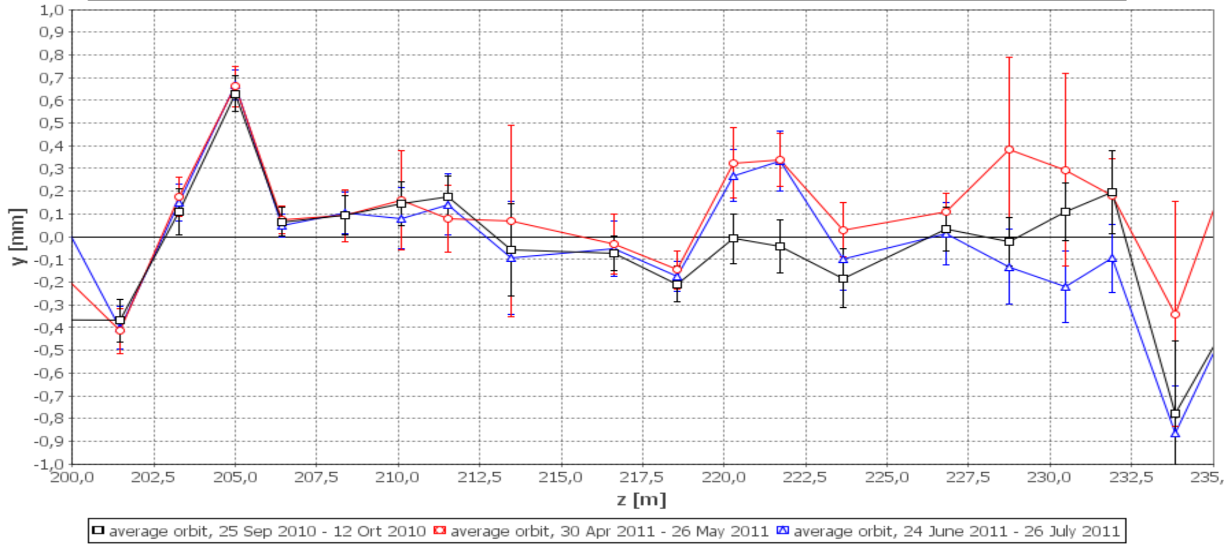
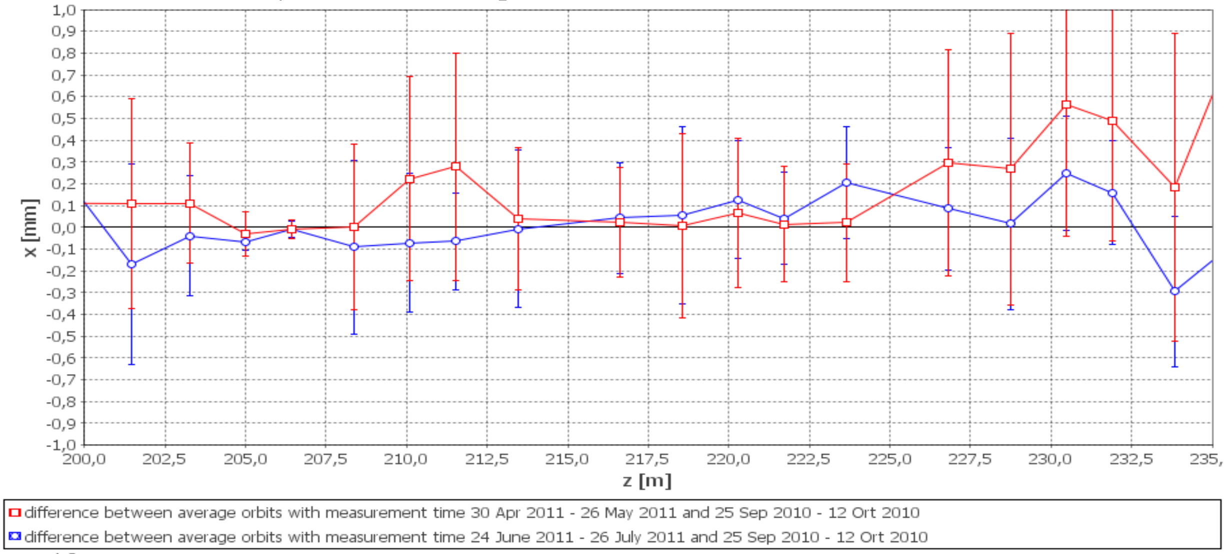


Figure 6. The difference between average orbits with measurement time:
30 Apr 2011 - 26 May 2011 and 25 Sep 2010 - 12 Ort 2010;
24 June 2011 - 26 July 2011 and 25 Sep 2010 - 12 Ort 2010



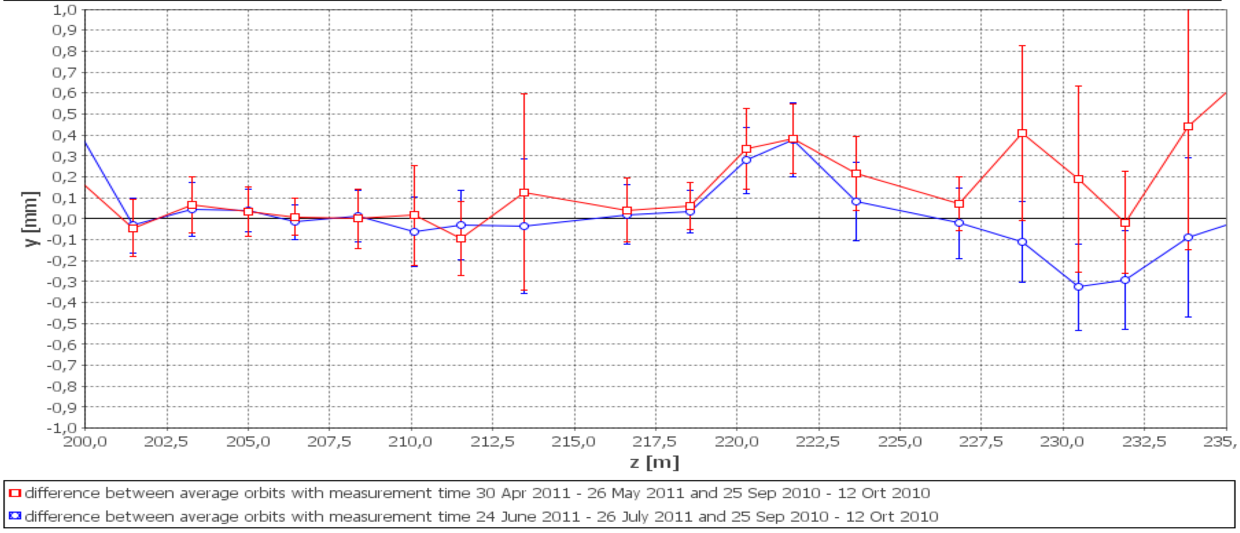


Fig.5;6 shows that taking into account standard deviation, the average orbits of electron bunches with different measurement time are the same(with the exception of Y measurement by BPMs located between 220 and 222 m).

The comparison of golden orbits taken with different energies (500, 700 and 950 MeV) and the comparison of golden orbits taken at 3 different time periods don't show significant differences.

Search of "golden" orbit independent of time, energy and charge

First we select data with E = [678; 710] MeV, $I_{ph} > 50$ µJ and measurement time from 27th June to 1st August 2011 and then we calculate the average orbit for both planes X and Y.

In order to estimate how close the orbits are to the average orbit for the selection defined above, we use the root mean square deviation (RMSD).

$$RMSD_x = \sqrt{\frac{1}{N_{und}} \sum_{j=1}^{N_{und}} (\widehat{x^j} - x^j)^2} \quad (1)$$

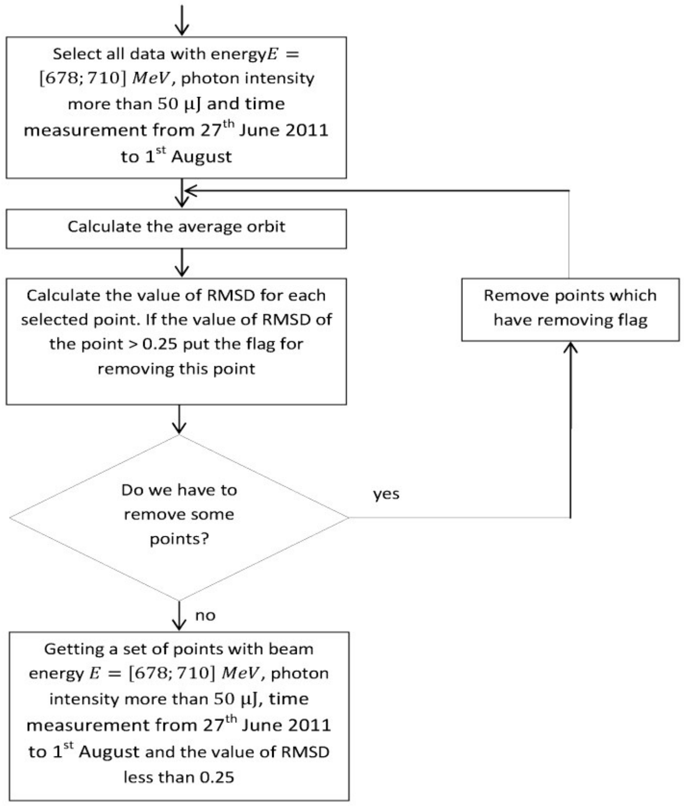
$$RMSD_y = \sqrt{\frac{1}{N_{und}} \sum_{j=1}^{N_{und}} (\widehat{y^j} - y^j)^2} \quad (2)$$

where j - index of BPM, N_{und} – number of BPMs installed at a distance of about [200; 230] m from RF gun, $\widehat{x^j}$ and $\widehat{y^j}$ is x and y coordinate of the average orbit of data selection pointed above, x^j and y^j is x and y coordinate of orbit of data we calculate RMSD.

We restrict the calculation of RMSD to the BPMs located in the undulators (between z = 200 and z = 230 m).

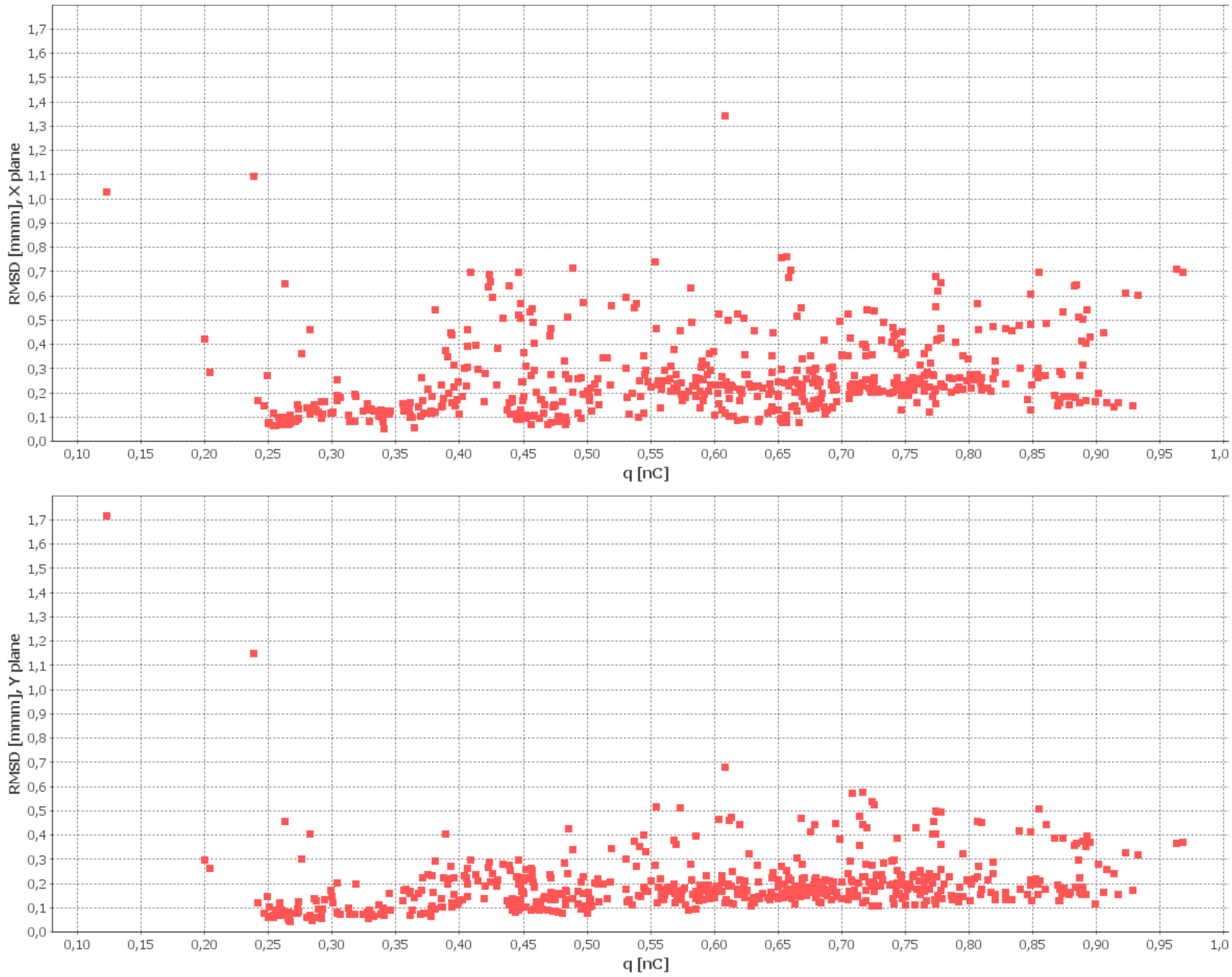
To get a candidate for golden orbit we start with the selection pointed above and choose only data with value of RMSD less than 0.25 mm. To do this we use the algorithm showed in Fig. 7. Number of points in this selection is equal to 65.

Figure 7. Algorithm for value of RMSD < 0.25 mm selection for data with E = [678; 710] MeV, $I_{ph} > 50$ µJ and measurement time from 27th June to 1st August 2011



Now we take all orbits in the database that have $I_{ph} > 50$ µJ (independent of beam energy, measurement time and bunch charge) and we calculate the RMSD with respect to the average orbit of 65 orbits selected above using the algorithm just mentioned. RMSD values thus obtained are shown in Fig. 8 as a function of bunch charge and in the Fig. 9 as a function of photon intensity.

Figure 8. RMSD values of all data with $I_{ph} > 50$µJ as a function of bunch charge



In Fig. 8 we can observe that RMSD values are between 0 and 0.2 mm for bunch charges below 0.36 nC (with some few exceptions) as compared with RMSD values for bunch charge above 0.36 nC which are spread up to 0.8 mm (in X plane).

This fact may indicate that a selection of orbits with low bunch charge less than 0.36 nC can give a good candidate for golden orbit independent of beam energy, measurement time and bunch charge.

Based on Fig. 8 we select all data with photon intensity more than 50 µJ and bunch charge less than 0.36 nC. Then using the algorithm showed on Fig.7 we select only data with photon intensity more than 50 µJ, bunch charge less than 0.36 nC and value of RMSD less than 0.2 mm. This selection gives the second candidate for “golden” orbit. Number of points in the selection just mentioned is equal to 68.

Figure 9. RMSD values of all data with $I_{ph} > 50$ μJ as a function of photon intensity

In Fig. 9 we observe that RMSD values have a larger spread if the values of the photon intensity are lower. Furthermore, most of orbits taken for $I_{ph} > 200$ μJ have RMSD values less than 0.3 mm in X plane and less than 0.2 mm in Y plane.

This fact may indicate that a selection taken with $I_{ph} > 200$ μJ can give a good candidate for golden orbit independent of beam energy, measurement time and bunch charge.

Based in Fig. 9 and applying the algorithm showed in Fig.7 we select data with high photon intensity more than 200 μJ and the value of RMSD less than 0.3 mm. This selection gives the third candidate for "golden" orbit. Number of points in the selection just mentioned is equal to 39.

We have three criteria to get a candidate for golden orbit. In order to find which candidate represents a "golden" orbit independent of measurement time, beam energy and bunch charge we plot histogram of RMSD (only in X plane) for all three criteria. The histograms are shown in the Fig. 10; 11; 12.

Figure 10. Histogram of RMSD for all data in the database with respect to the average for first criteria data mentioned above (X plane)

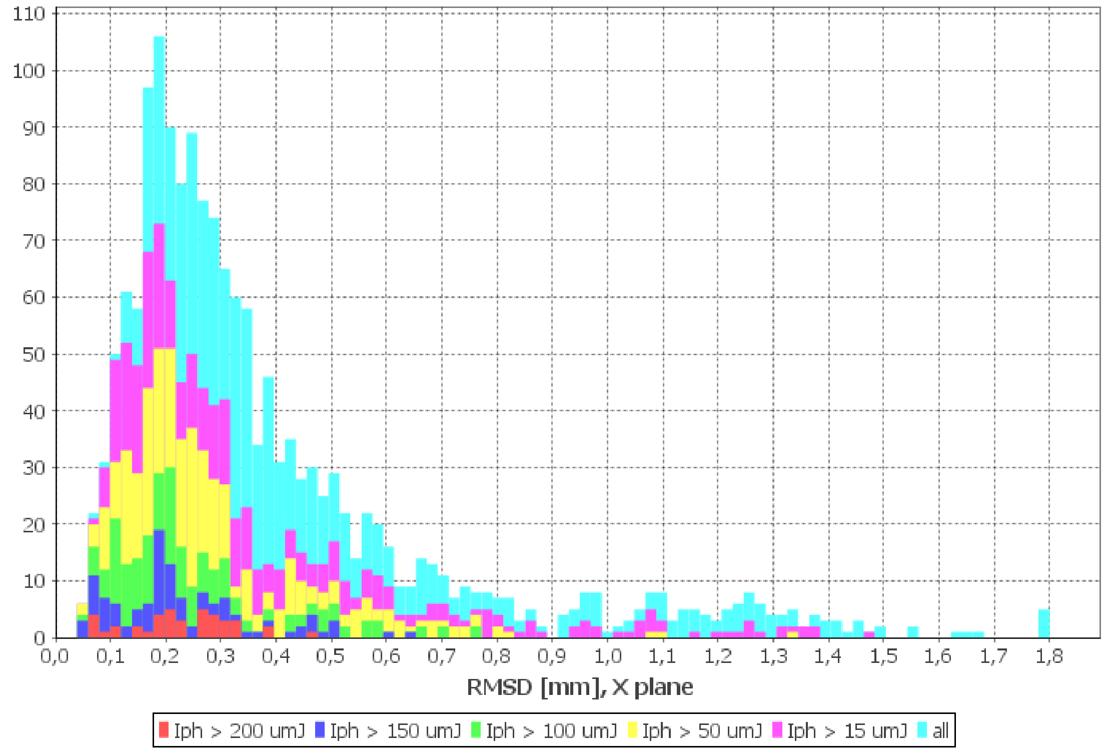


Figure 11. Histogram of RMSD for all data in the database with respect to the average for second criteria data mentioned above (X plane)

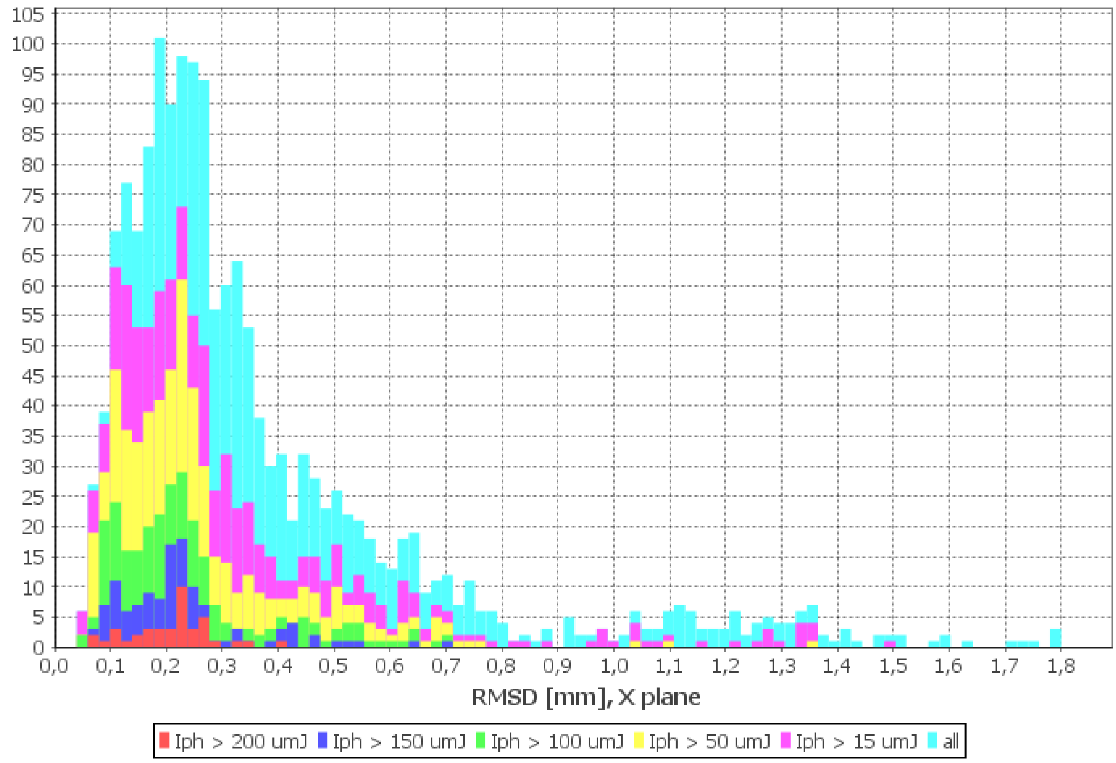
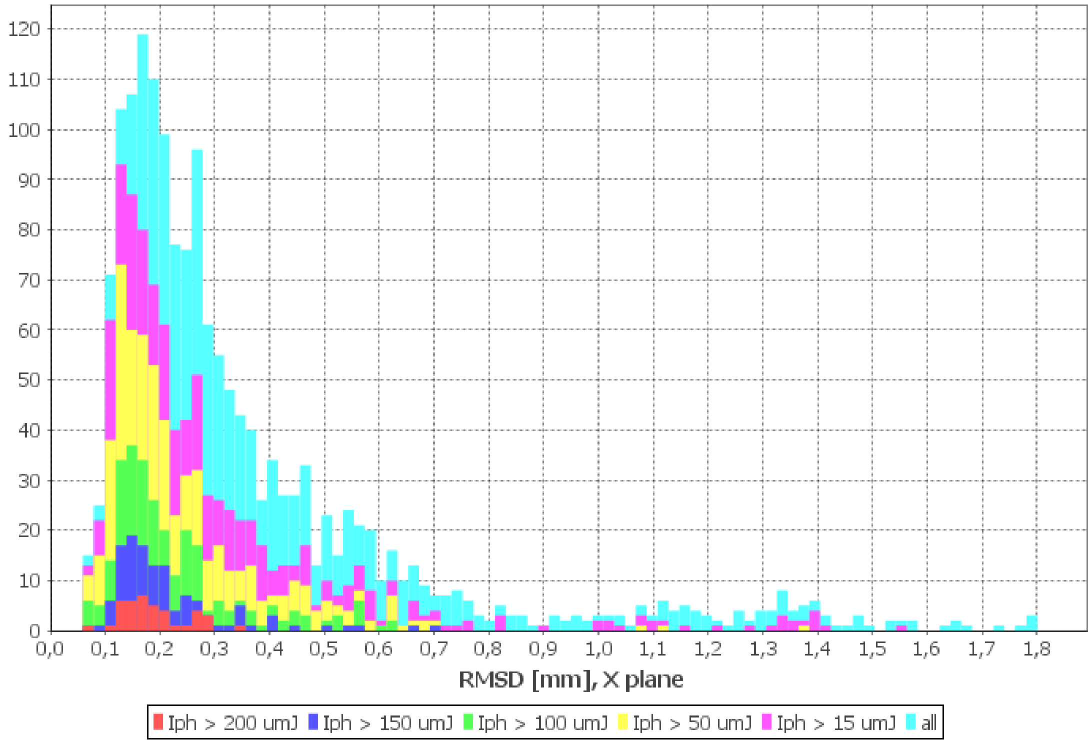


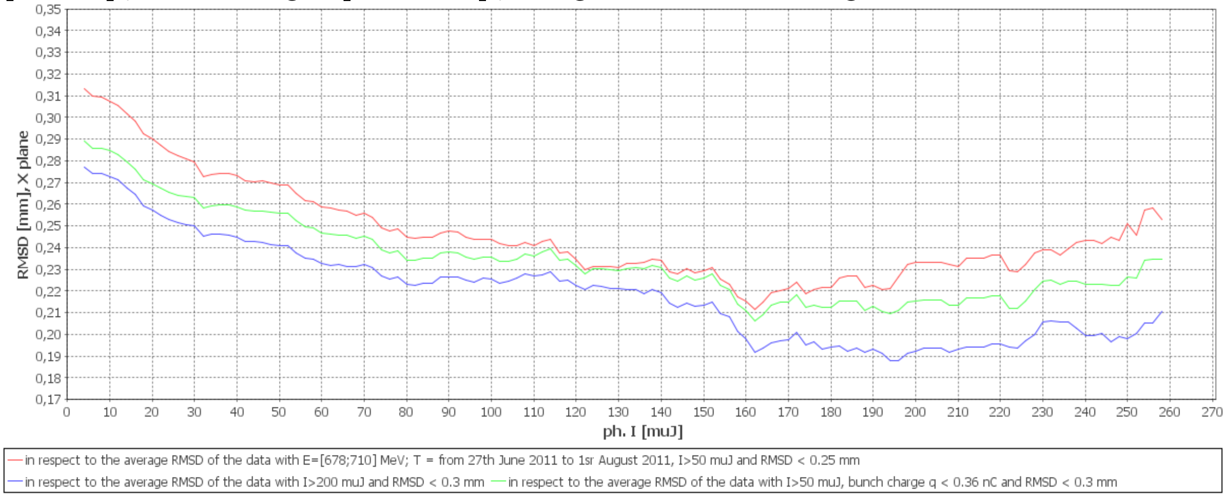
Figure 12. Histogram of RMSD for all data in the database with respect to the average for third criteria data mentioned above (X plane)

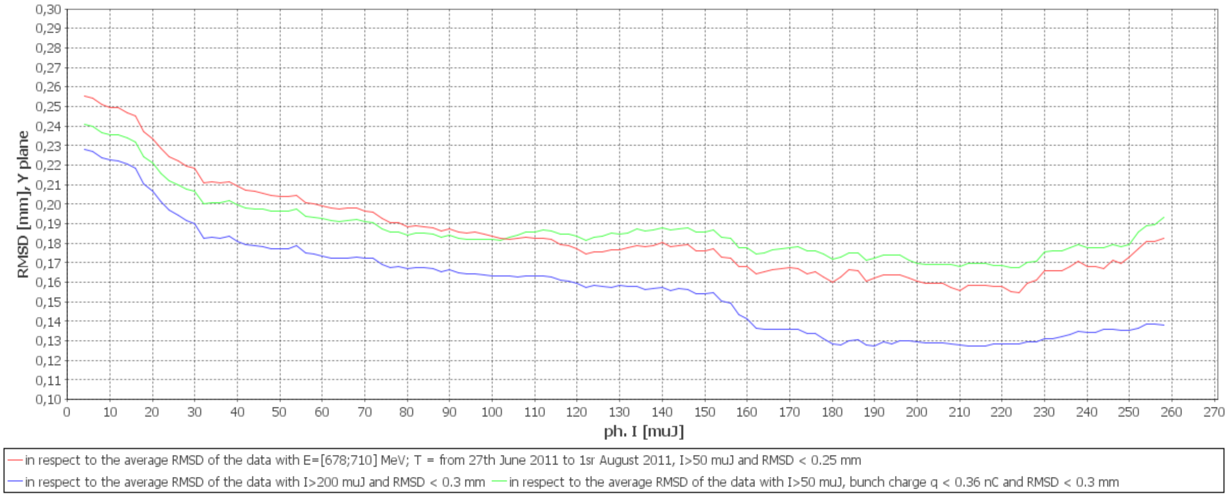


In Fig. 10; 11; 12 we can observe that the distribution of RMSD values of each group of data with the same photon intensity range are different for three "golden" orbit candidates. In Fig. 10; 11; 12 the RMSD distribution is shifted to the right relative to Y axis. The explanation of these shifts is shown in Appendix 1.

We calculate the average RMSD value for each photon intensity range with a step of 2 μJ (we start from [2; 500] μJ range and end at [260; 500] μJ range) for each of three "golden" orbit candidates.

Figure 13. The average RMSD values for each photon intensity range starting from [2; 500] μJ and ending at [260; 500] μJ range for each of three "golden" orbit candidates





Based on Fig. 13 we can see that both for X and Y planes the average RMSD values for all photon intensity ranges pointed above are lowest in case of third criteria (data with high photon intensity more than 200 µJ and the value of RMSD less than 0.3 mm). In this case the average value of RDMS is about 0.195 mm for X plane and about 0.125 mm for Y plane for data with high photon intensity more than $I_{ph} > 180$ µJ.

This fact may indicate that the third selection taken with $I_{ph} > 200$ µJ and the value of RMSD less than 0.3 mm seems to be the best candidate of the three considered for "golden" orbit independent of beam energy, measurement time and bunch charge.

In order to show clearly that "golden" orbit is independent of time, beam energy and bunch charge we plot (only X plane) RMSD values with respect to the "golden" orbit data as a function of bunch charge for three ranges with high photon intensity (see Fig. 14); the history of RMSD values with respect to the "golden" orbit data for six photon intensity ranges (see Fig. 15); RMSD values with respect to the "golden" orbit data as a function of beam energy for six photon intensity ranges (see Fig. 16).

Figure 14. RMSD values with respect to the "golden" orbit data as a function of bunch charge for three ranges with high photon intensity: [100; 150] µJ; [150; 200] µJ; [200; 500] µJ (X plane)

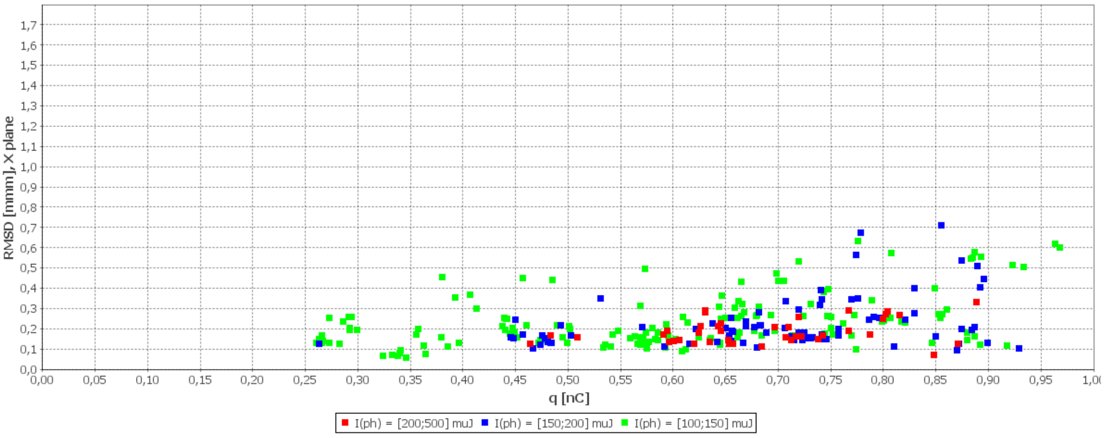


Figure 15. The history of RMSD values with respect to the “golden” orbit data for six photon intensity ranges: [0; 15] μJ; [15; 50] μJ; [50; 100] μJ; [100; 150] μJ; [150; 200] μJ; [200; 500] μJ (X plane)

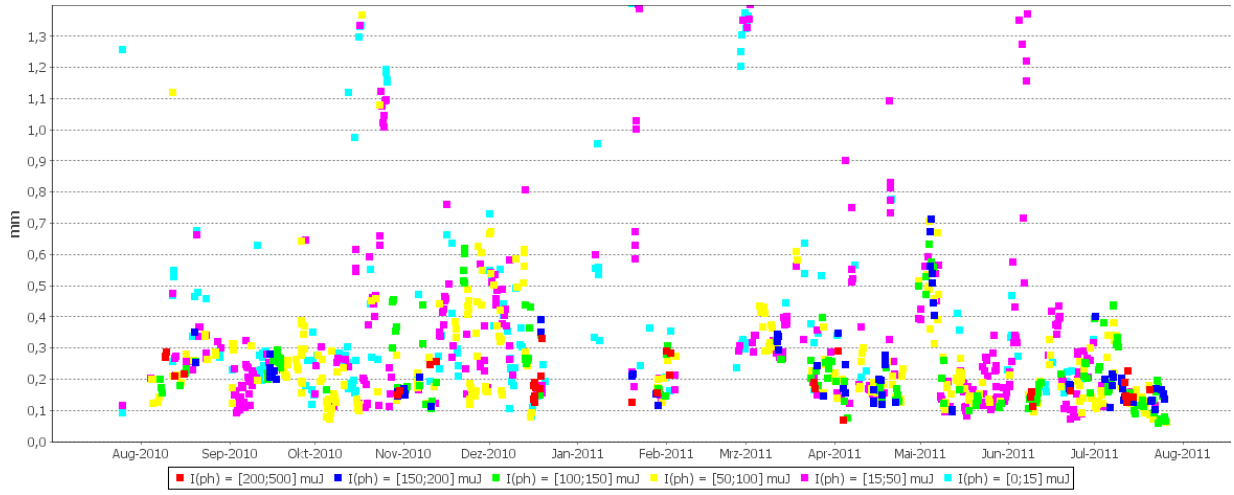
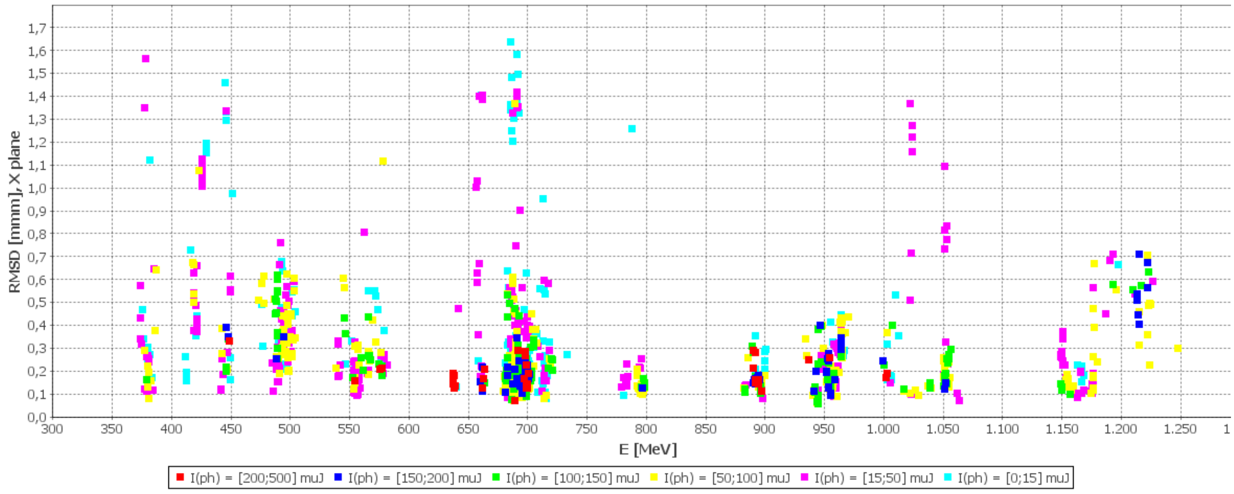


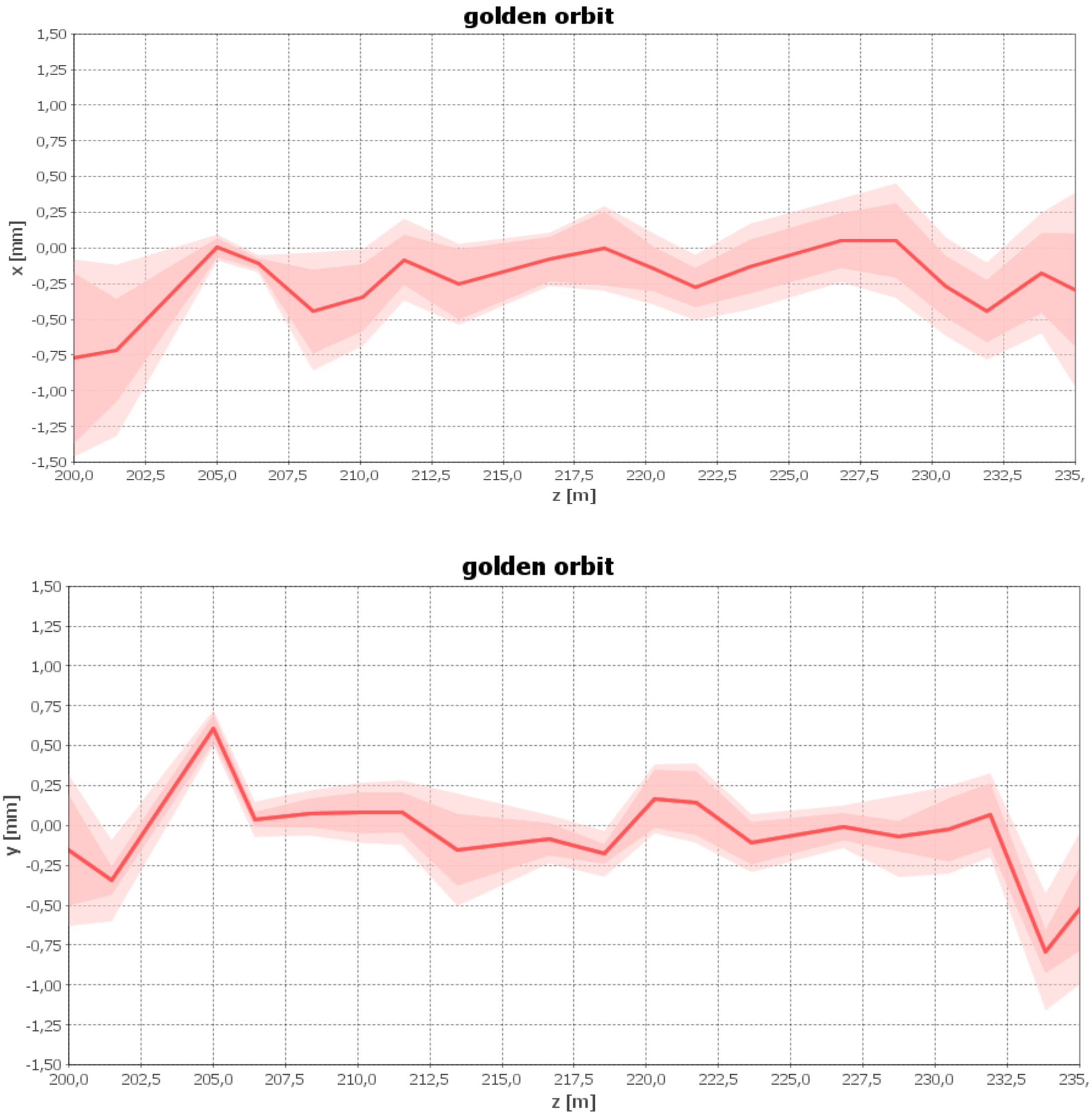
Figure 16. RMSD values with respect to the “golden” orbit data as a function of beam energy for six photon intensity ranges: [0; 15] μJ; [15; 50] μJ; [50; 100] μJ; [100; 150] μJ; [150; 200] μJ; [200; 500] μJ (X plane)



In Fig. 14; 15; 16 we can observe that most data with high photon intensity more than 100 μJ (marked as red, dark blue and green) have lower RMSD values than the data with photon intensity less than 100 μJ (marked as magenta, cyan and yellow) with the exception of a group of data taken at beginning of May 2011 for beam energies around 1.2 GeV. These facts clearly show that the “golden” orbit is independent of measurement time (from August 2010 to August 2011), beam energy (from 450 MeV to 1200 MeV) and bunch charge (from $0.26\ nC$ to $0.97\ nC$).

The "golden" orbit is shown in Fig. 14. In Fig. 14 the standard deviation for data selection with $I_{ph} > 200$ μJ and RMSD < 0.3 mm from the "golden" orbit (dark red) and standard deviation for data selection with $I_{ph} > 50$ μJ and RMSD < 0.3 mm from the "golden" orbit (light red) are shown.

Figure 17. The "golden" orbit, standard deviation for data with $I_{ph} > 200$ μJ and RMSD < 0.3 mm from the "golden" orbit (dark red) and standard deviation for data with $I_{ph} > 50$ μJ and RMSD < 0.3 mm from the "golden" orbit (light red)



Conclusion

In this article we show that orbit data taken in Free Electron Laser (FLASH accelerator) with beam energy selection and with measurement time selection do not have significant differences. We analyze three candidates for a “golden” orbit independent of beam energy, measurement time and bunch charge and select the best one: the “golden” orbit is an average orbit of data with photon intensity $I_{ph} > 200$ μJ and the value of RMSD < 0.3 mm.

Reference

[1] FLASH website: http://flash.desy.de/.

Appendix 1: distribution of RMSD

In this appendix we want to demonstrate RMSD distribution theory that explains why the histograms in the Fig. 10; 11; 12 have RMSD values distribution starting from nonzero value (another words, the RMSD spreading is shifted to the right in relative to Y axis in the Fig. 10; 11; 12) and show how we can calculate the RMSD standard deviation value in case of Gaussian distribution of orbit’s X and Y coordinate values.

Assume that we have a large finite quantity of orbits. X and Y coordinate values of these orbits are selected randomly under the Gaussian distribution with mean value is equal to μ and the standard deviation value is equal to σ. N BPMs settled in the undulator measured the X and Y coordinates of the orbits. To simplify the theory review we will take a look only in one plane, for example, X plane.

For each orbit every BPM measures the x_i coordinate, where i – index of BPM.

The mean value of x coordinate for all BPMs

$$\hat{x} = \frac{x_1 + x_2 + \cdots + x_N}{N}$$

where N-number of BPMs.

The residuals are

$$\hat{\varepsilon}_i = x_i - \hat{x}, i = 1 \dots N$$

The sum of squares of the residuals, divided by σ^2, has a distribution which is equal to the chi-square distribution with $N - 1$ degrees of freedom (Cochran’s theorem)

$$\sum_{i=1}^{N} \frac{(x_i - \hat{x})^2}{\sigma^2} \sim \chi^2_{N-1}$$

$$Var\left(\sum_{i=1}^{N}\frac{(x_i-\hat{x})^2}{\sigma^2}\right)=Var(\chi^2_{N-1})=2(N-1)$$

We apply $Var(ax)=a^2Var(x)$ to get:

$$Var\left(\sum_{i=1}^{N}\frac{(x_i-\hat{x})^2}{N-1}\right)=Var\left(\frac{\sigma^2}{N-1}\sum_{i=1}^{N}\frac{(x_i-\hat{x})^2}{\sigma^2}\right)=\frac{\sigma^4}{(N-1)^2}Var\left(\sum_{i=1}^{N}\frac{(x_i-\hat{x})^2}{\sigma^2}\right)$$

$$Var\left(\sum_{i=1}^{N}\frac{(x_i-\hat{x})^2}{N-1}\right)=\frac{2}{(N-1)}\sigma^4$$

$$RMSD=\sqrt{\sum_{i=1}^{N}\frac{(x_i-\hat{x})^2}{N}}\Longrightarrow Var(RMSD^2)=\frac{2}{(N-1)}\sigma^4$$

Taking into account formula $Var\big(f(x)\big)\simeq(f'(E(x)))^2Var(x)$, where $E(x)$ – expected (mean) value, we get

$$Var(RMSD^2)\simeq\big(2E(RMSD)\big)^2Var(RMSD)\Longrightarrow$$
$$\Longrightarrow Var(RMSD)\simeq\frac{1}{(2E(RMSD))^2}Var(RMSD^2)$$

$$\sigma_{RMSD}=\sqrt{Var(RMSD)}\simeq\frac{1}{E(RMSD)}\frac{\sigma^2}{\sqrt{2(N-1)}}\qquad(1.1)$$

Example 1:

We choose 10^5 orbits. X and Y coordinate values of these orbits are selected randomly under the Gaussian distribution with mean value is equal to zero and the standard deviation value is equal to σ = 0.2 mm. N = 18 BPMs settled in the undulators measured the X and Y coordinates of the orbits.

$N = 18;\ \sigma = 0.2\ mm;$

In this case we have:

$E(RMSD) = 0.197\ mm;$

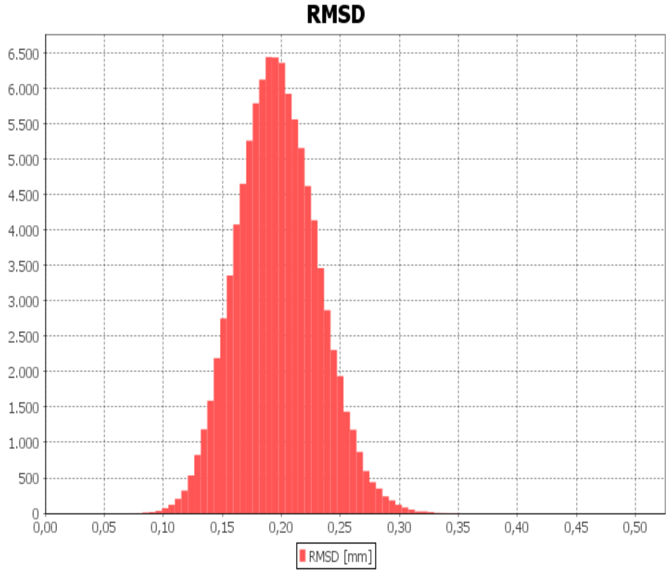
$\sigma_{RMSD}(eq. 1.1) = 0.0348\ mm$

The simulation gives us :

$\sigma_{RMSD}(simulation) = 0.0341\ mm$

The difference between the theory and simulation value is about 2%.

Fig. 1.1. The RMSD distribution in case of $N = 18;\ \sigma = 0.2\ mm;$



Example 2:

$N = 9;\ \sigma = 0.2\ mm;$

In this case we have:

$E(RMSD) = 0.194\ mm;$

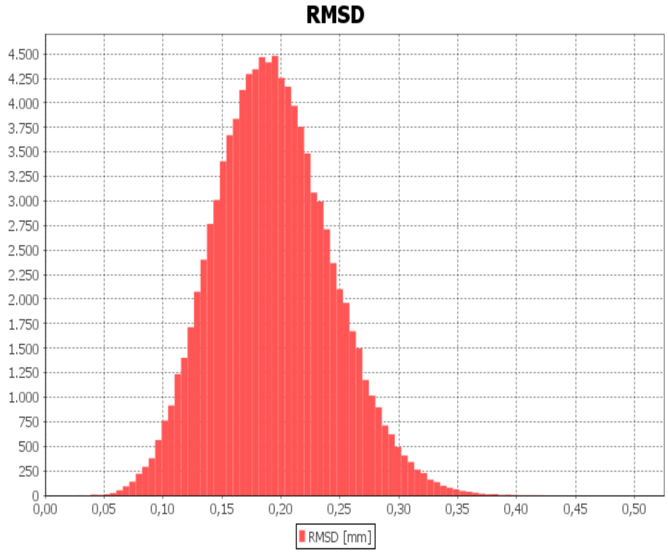
$\sigma_{RMSD}(eq. 1.1) = 0.0515\ mm$

The simulation gives us :

$\sigma_{RMSD}(simulation) = 0.0493\ mm$

The difference between the theory and simulation value is about 4%.

Fig. 1.2. The RMSD distribution in case of $N = 9;\ \sigma = 0.2\ mm;$



Example 3:

$N = 3;\ \sigma = 0.2\ mm;$

In this case we have:

$E(RMSD) = 0.177\ mm;$

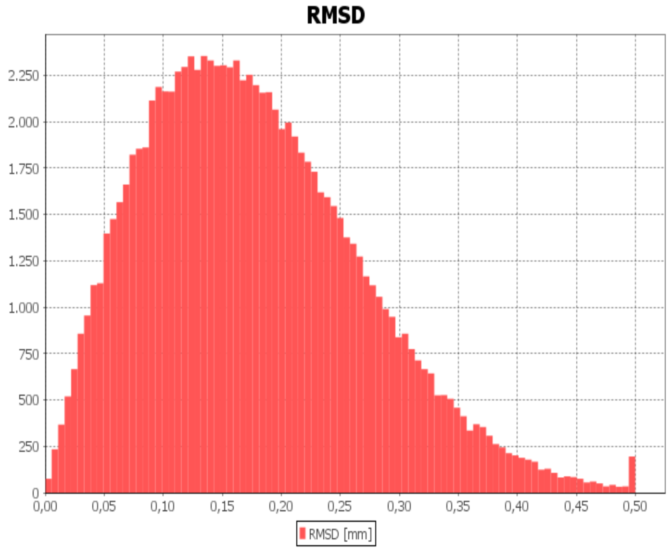
$\sigma_{RMSD}(eq. 1.1) = 0.113\ mm$

The simulation gives us :

$\sigma_{RMSD}(simulation) = 0.093\ mm$

The difference between the theory and simulation value is about 17%.

Fig. 1.3. The RMSD distribution in case of $N = 3;\ \sigma = 0.2\ mm;$



In Fig. 1.1; 1.2; 1.3 we can observe that the distribution of RMSD values moves away from 0 as N increase. The reason is following: the probability to have a value of RMSD near 0 is equal to the probability to have all $\{x_i\}$ values around zero at the same time. Therefore, $P(RMSD\ around\ zero) = [P(x_i\ around\ zero)]^N$. Then for increasing N value the probability decreases as a power function.

The common principle of RMSD distribution shifting can also be simply explained on the example of coin. It is two possibilities when the coin is thrown: it falls front faced (the probability is 0.5) or it falls back faced (the probability is also 0.5). If we throw the coin two times the probability it falls the same faced all two times is 0.5^2. That means that we can expect that this event occur every fourth time we throw it. If we throw the coin ten times the probability it falls the same faced all times is 0.5^{10}. That means that the number of such events approach to zero and the histograms of these events is shifted to the right.