Dispersion study at FLASHForward

Bohdan Dudar, Taras Shevchenko National University of Kyiv, Ukraine

September 5, 2018

Abstract

In this report dispersion analysis at FLASHForward plasma-wakefield acceleration experiment, DESY is presented. Dispersion measurements during a recent beam time were performed. Reasons for non-zero residual dispersion are analyzed with help of numerical simulations. Different approaches to minimize dispersion are studied. A scintillator screen in dispersive section was used to cross-check the dispersion measurement and to extract the beam energy distribution.

Contents

1 Introduction

At the moment the energy frontier of particle physics is few TeV, but colliders capable of reaching that energies (for instance LHC) are costly and time-consuming to build. It is therefore important to explore new methods of accelerating particles to high energies.

During the recent years Plasma Wake Field Acceleration (PWFA) technology has been rapidly developing. Plasma-based accelerators are particularly attractive because they are capable of producing accelerating fields that are orders of magnitude larger than those used in conventional colliders. Therefore, this can substitute existing accelerators with more powerful and give another push for accelerator applications in many areas.

FLASHForward is an experiment which is built at DESY in order to tackle key PWFA challenges, such as beam quality and stability. To start PWFA experiments low-emitance, short and tightly focused electron beam has to be achieved.

Dispersion is one of the factors that influences beam size. It's definition is dependence of the transverse coordinate of particles on the energy. Due to the momentum chirp created in a radio frequency (RF) cavities, needed for a bunch compression, beam particles with large energy deviation will deviate from the ideal trajectory. As a result it will make beam larger, so dispersion has to be minimized in order to achieve small beam.

As an example, for an energy spread of $\delta = 0.01$ and beam dispersion of $\eta = 20$ mm beam transverse size becomes bigger by $\Delta x = \eta \cdot \ \delta = 20\ mm \cdot 0.01 = 200\ \mu$m. For PWFA experiments electron beams have to reach transverse size of less than 10 μm.

In this study the dispersion was measured and influence of different parameters on dispersion was studied as well. Several dispersion minimization approaches were tested. Energy spectrum measurement in the dispersive section of FLASHForward was performed.

2 FLASHForward

FLASHForward[1] is a PWFA experiment at Deutsches Elektronen-Synchrotron (DESY) in Hamburg. The goal of the experiment is to produce high energetic electrons (> 1.5 GeV) within just a few centimeters of plasma and demonstrate their high-quality and low-emitance. First beams are successfully transmitted through the beamline in 2017. The experiments are ongoing now.

The beamline is approximately 50 m long and divided into 4 sections: extraction (EXTR), compression (COMP), matching and final focusing (MAFF) and diagnostics (DIAG). Along the beamline 12 beam position monitors (BPMs) are situated which will be used in this analysis. Also, for reader's information, can be noted that plasma cell is situated at the beginning of the DIAG section (in the end of the MAFF section). Accelerating RF cavities which were used to vary energy gain are placed in the FLASH tunnel, which schematically pictured in Figure 1.

More detailed description of the FLASH facilities concerned reader can find elsewhere [2].

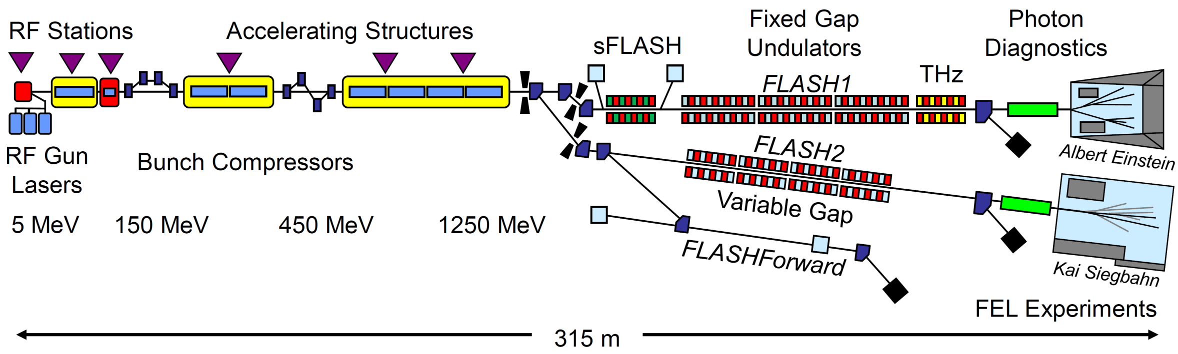

Figure 1: Schematic layout of FLASH. Not to scale.

3 Theory

For charged particles in an accelerator we can write the basic equation of motion in the linear approximation - Hill's equation, as follows [3] :

$$x(s)'' + K(s)x(s) = \frac{1}{\rho} \cdot \frac{\Delta p}{p_0}, \tag{1}$$

where $x(s)$ is transverse coordinate of a particle as function of s - longitudinal position in the FLASHForward beamline, $\frac{\Delta p}{p_0}$ - relative particle momentum deviation $\Delta p = p - p_0$ from reference momentum p_0, $K(s) = -k(s) + \frac{1}{\rho^2(s)}$, with k(s) - focusing strength and $\rho(s)$ - bending rating of elements as function of longitudinal position in the beamline.

This is a second order linear inhomogeneous differential equation. The solution will be a linear combination of a general solution for homogeneous equation and some particular solution for inhomogeneous equation and it can be written as follows:

$$x(s) = x_h(s) + x_i(s) = C(s)x_0 + S(s)x_0' + x_i = C(s)x_0 + S(s)x_0' + \eta(s)\frac{\Delta p}{p_0} \tag{2}$$

Here x_0 and x_0' are initial values of $x_h(s)$ at some starting reference point $s = s_0$, and $C(s)$, $S(s)$ - are two independent cosine-,sine-like solutions of homogeneous equation. $C(s)$ and $S(s)$ fulfill the following boundary conditions: $C(0) = 1$, $C'(0) = 0$, $S(0) = 0$,

$S'(0) = 1$ x_i - partial solution for inhomogeneous equation.

Because x_i is proportional to $\frac{\Delta p}{p_0}$ we can write it as $x_i = \eta(s) \cdot \frac{\Delta p}{p_0}$. And thus to introduce the $\eta(s)$ - dispersion trajectory. Physical meaning of this quantity is transverse shift Δx for particles with a relative momentum deviation $\frac{\Delta p}{p_0}$ from the reference momentum p_0.

Particles in the electron beam have some momentum spread by it's nature. But also big amount of it comes from the fact that we create so called momentum chirp in RF cavities. It is energy spread $\delta = \frac{\Delta E}{E_0}$ dependence on longitudinal position of a particle in the beam. Momentum chirp is needed in order to compress the electron beam.

4 Measurements

To measure the dispersion in FLASHForward beamline, beam position data was used as recorded by beam position monitors (BPMs) during a scan (gradual changing) of the energy gain in one of the RF cavities in FLASH called ACC45. Dependencies of the beam position as a function of the energy gain can be used to extract the dispersion. In particular, the 1st order dispersion was studied and obtained from the fit of 2nd order polynom to the data[1].

To access data from the detectors during the experiment the Distributed Object Oriented Control System (DOOCS) is used. It makes data accessible with python, matlab, etc. scripts. More information about DOOCS can be found here [4].

Also, with recently provided data acquisition (DAQ) system for FLASHForward experiment, it is possible to access data at DAQ server and continue analysis after the experiment has been finished. DAQ is a system which saves the data after reading it from DOOCS during the experiment.

By using matlab scripts values of the beam energy gain in the ACC45 RF cavity module and from x and y axes of all BPMs were read offline. Examples of the signals are depicted in the Figure 2.
As a next step, the dependencies of BPM's positions versus energy gain should be plotted and fitted with polynomial function. It was done for both x and y axes of all BPMs. In Figure 3 fits for all BPMs only for x axis are shown.
The linear order fit parameters for every BPM represent dispersion as a function of BPM positions in the beamline. Measured dispersion is shown in the Figure 4 as black dots. Red line represents dispersion simulated in the elegant[5] program for a perfectly constructed accelerator without any error which we want to achieve as close as possible. As can be seen from Figure 4, horizontal dispersion stays limited and doesn't diverge ($\eta_x < 20$ mm) through MAFF and DIAG sections and can be reduced further with

[1]Fit with higher order polynomials also possible and can be studied.

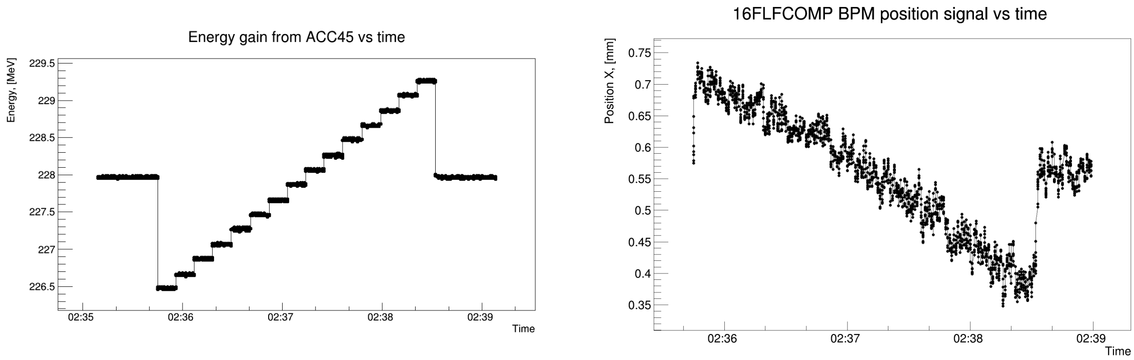

Figure 2: Energy gain of ACC45 and beam horizontal position in 16FLFCOMP BPM recorded by the DAQ system.

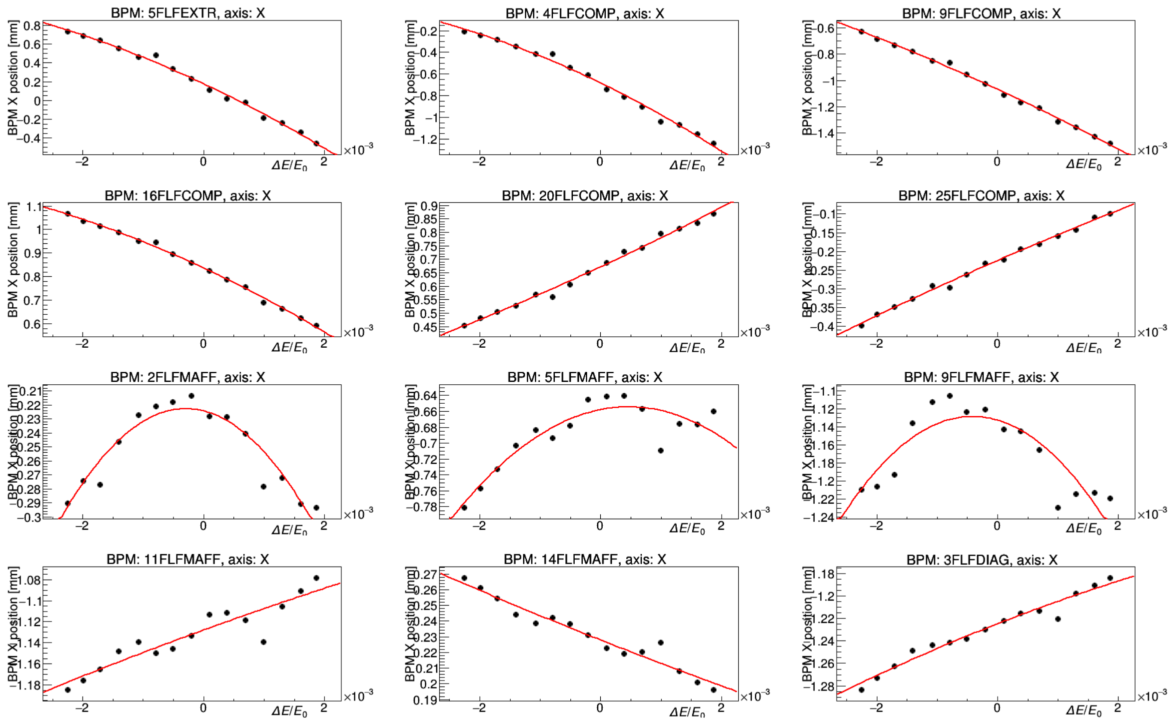

Figure 3: Beam horizontal position as a function of energy gain for all BPMs in FLASH-Forward.

more precise quadrupoles' current variation. At the same time, vertical dispersion is not closed and grows rapidly. It is necessary to suppress vertical dispersion for further plasma experiments to the absolute values of order 1 mm. This will result in the additional beam size less than 10 μm for momentum deviation $\frac{\Delta p}{p_0} = \delta = 0.01$.

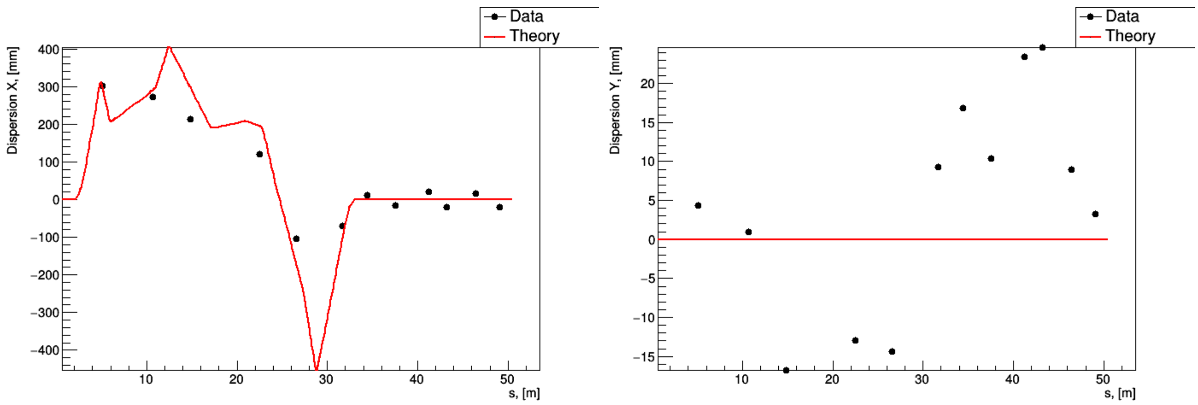

Figure 4: Measured horizontal and vertical dispersion distribution along the FLASHForward beamline.

5 Simulations

5.1 Reasons for dispersion in FLASHForward

First of all, we have to understand the reasons that cause a large vertical dispersion in MAFF and DIAG sections, in order to be able to find a procedure to minimize it. To study these reasons, simulations have been made in the elegant program. In simulations dispersion was calculated the same way it was obtained in the experiment using centroid beam coordinates at BPMs' positions as a function of the beam energy.

The effects that can cause the residual dispersion:

- **Misalignment of horizontal and vertical quadrupole positions** - If quadrupole center is not situated at the center of the design (ideal) beam trajectory which has influence on dispersion in it's matrix elements. (at FLASHForward magnets are aligned to precision better of < 300 μm)
- **Horizontal and vertical beam position shifts at the start of the beamline** - The beam shifted relatively to designed trajectory will be affected by the same effects as with quadrupoles misalignment.
- **Quadruple focusing strength (K1) parameters' errors** - closed horizontal dispersion is achieved by precise setup of all quadrupoles K1 parameters, so any deviation caused by current instability, current measuring device errors, etc., will influence dispersion as a result.
- **Residual dispersion in FLASH2** - if dispersion not properly closed in FLASH2 beamline upstream FLASHForward, it will propagate to FLASHForward and will have an effect there.

Discussed above reasons for dispersion are simulated in elegant and presented in Figure 5.

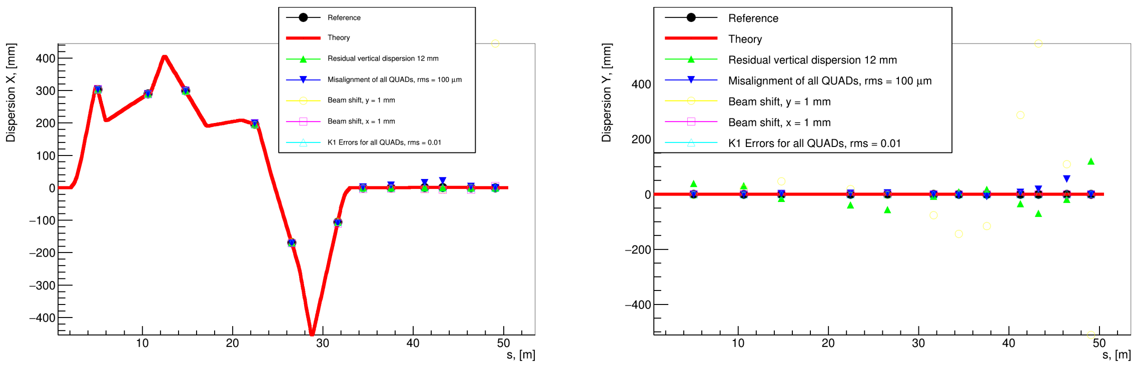

Figure 5: Dispersion in FLASHForward with various effects simulated.

As can be seen, vertical beam shift causes the largest dispersion in the DIAG section due to the big tested shift value (1 mm). Residual dispersion from the FLASH2 beamline shows some influence and causes the dispersion along the FLASHForward beamline as well. Simulated vertical dispersion caused by residual dispersion in FLASH2 grows rapidly in MAFF and DIAG sections, similar to one been observed during the experimental dispersion measurements. Also misalignment of quadrupoles and vertical beam shift seem to cause some visible effect.

5.2 Dispersion correction

A possible way to minimize a non-zero dispersion is to tune currents[2] in the elements of the beamline (kickers, quadrupoles, sextupoles) has to be varied to find optimal values. So this section of report will be about current optimization using simulations to reduce the dispersion. Optimization simulations made with optimization functions included in the elegant program.

Successful optimization requires understanding of which elements currents should be varied, what range and step length should be set. Optimization simulation takes a long time, so these parameters had been chosen to achieve not so long ($\sim$ 1 day) processing time and to cover as many elements and ranges as possible. Table 1 shows the variation of parameters for every element respectively.

The goal of all further optimization simulations to minimize[3] dispersion caused by misalignment of quadrupoles in the COMP section of the FLASHForward at both x and y axes distributed as Gaussian with rms = 100 μm for every quadrupole.

[2] In the simulation program not current was varied but KICK, K1, K2 parameters of kickers, quadrupoles, sextupoles. In experiment needed parameters can be easily reproduced varying current.

[3] As a minimization target was set a variable: $\eta^2_{x,BPM1} + ... + \eta^2_{x,BPM12} + 3 \cdot (\eta^2_{y,BPM1} + ... + \eta^2_{y,BPM12})$. Others minimization criterions need further studies.

Table 1: Table of parameters scans information used for optimization.

Element	Lower limit	Higher limit	Step	Units
Kicker, KICK	$-5 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$1 \cdot 10^{-5}$	Rad
Quadrupole, K1	-5	5	0.05	$1/m^2$
Sextupole, K2	-50	50	0.5	$1/m^3$

The following optimization setups were tested:

- variation of K1 parameters of quadrupoles in COMP section.
- variation of K2 parameters of all sextupoles .
- variation of KICK parameters of all kickers in COMP section.
- variation of KICK parameters of all kickers in COMP section. When dispersion caused by residual dispersion in FLASH2, not quadrupoles misalignment.

The results of optimization setups can be seen in Figure 6. All optimization setups were made for both η_x and η_y with weights 1:3 respectively in order to give vertical dispersion some priority over the horizontal dispersion. Magnitude of 3 was chosen arbitrary.

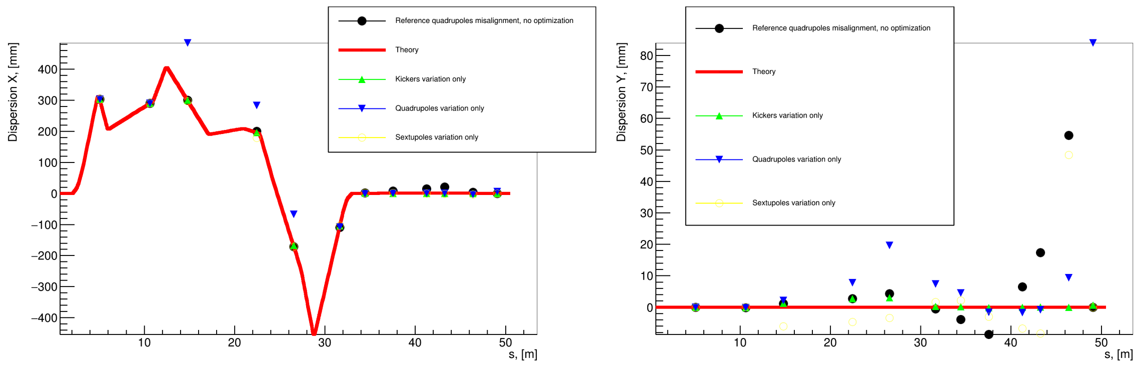

Figure 6: Dispersion in FLASHForward caused by quadrupoles misalignment with different optimization approaches.

Also influence of quadrupoles and sextupoles variation on η_y can be seen and therefore concluded that it doesn't solve the problem of non-zero vertical dispersion in MAFF-DIAG sections. With kickers it is possible to set it almost to zero with improved values of η_x as well. But kickers also needed to keep a beam in the center of the beamline, which may be problem to set these parameters in practice. Still this result may be useful as approximate guide for needed parameters values.

With this success, kickers were tested to minimize dispersion caused by residual dispersion from the FLASH2. But as can be seen in Figure 7 varying only kickers parameters not enough to close η_y and it still remain divergent and even gets bigger. It means that to close residual dispersion another optimization algorithm should be provided and more studies are needed.

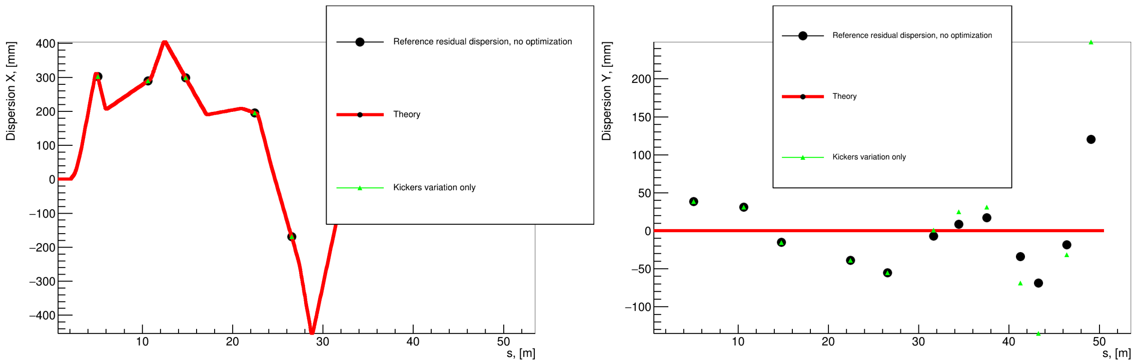

Figure 7: Dispersion in FLASHForward caused by residual disp. with only kickers' parameters variation.

6 Comparison of energy spectrum received by screen in COMP section and two spectrometers

The second part of the work - a test of agreement of energy spectrum obtained by using screen in the COMP section (14FLFCOMP), spectrometer situated in FLASH beamline (LOLA) and spectrometer situated in the end of FLASHForward beamline in DIAG section called 3FLFDIAG. Data from 14FLFCOMP screen was measured and stored in the DAQ system during the ACC45 energy gain scan. So we can use the same method to calculate shifts of the beam as a function of energy and convert horizontal axis to the energy scale using the dispersion, so that we can see the beam energy deviation on a screen and compare it to the spectrometers LOLA in the FLASH beamline and 3FLFDIAG spectrometer at the end of FLASHForward. It gives us an opportunity to check correspondence between 2 spectrometers and the screen data, to check is everything is working fine so these elements can be used in further studies or they have to be corrected, substituted, repaired, etc.

As written above calculating beam center shifts as function of energy gain we can obtain dispersion which depicted in Figure 8.
Calculating beam position without additional energy gain from ACC45 ($\sim$ 228 MeV in ACC45). And translating the pixel shift into an energy shift. By using the dispersion we obtain energy distribution of a beam.
It should has been noted that beam has his own geometrical size which has nothing to do

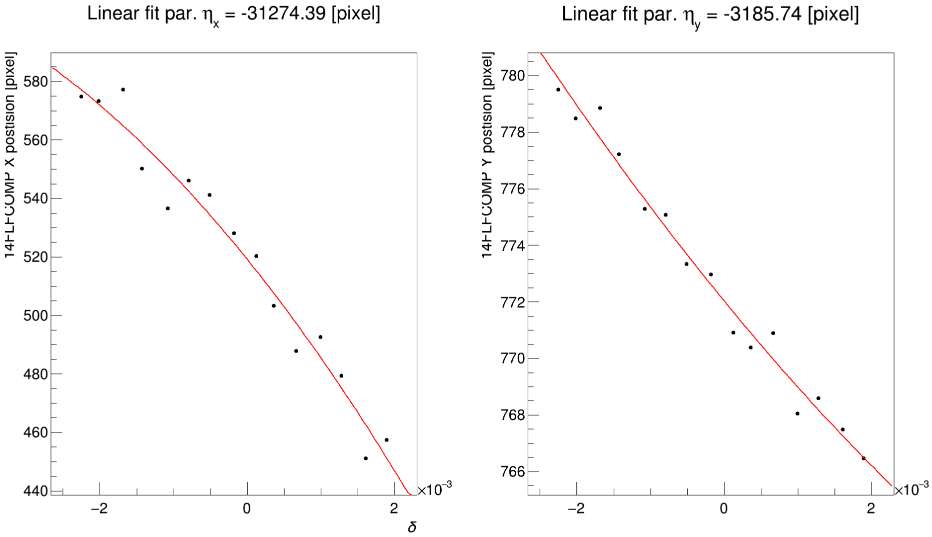

Figure 8: Dispersion at 14FLFCOMP calculated using screen data.

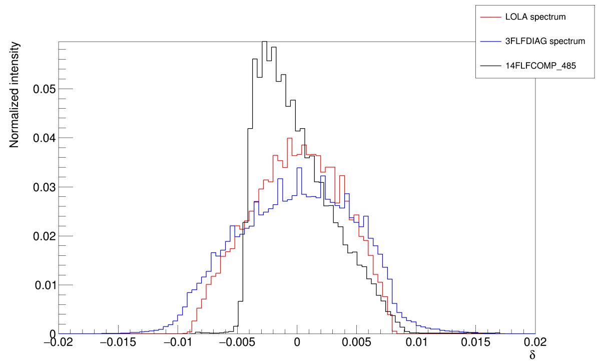

Figure 9: Beam energy distribution obtained in 14FLFCOMP, 3FLFDIAG and LOLA.

with energy deviation[4]. For energy distribution only horizontal axis dispersion was used because it results 10 times bigger than vertical one, so geometrical size of the beam can be negligent. Nevertheless, the beam size will cause some discrepancy in the final results.

In Figure 9 we see comparison between spectrometer signals and obtained 14FLFCOMP screen results. As we can see by far, agreement is questionable so further studies are needed to investigate the reasons. Is it fault of spectrometers or just transition through the beamline changes the beam and spectrometers are fine.

[4]It wasn't taken into account here with an assumption that the beam size relatively small to the size made by energy deviation. Nevertheless, for our purposes comparison of the shapes of the distribution is needed, not absolute values.

7 Summaries

In this work, the dispersion in FLASHForward electron beam line was measured. This was done offline, using the FLASH data-acquisition system for the first time, and the results agree to the online tools. A large vertical non-zero dispersion in the non-dispersive section directly upstream of the plasma cell was observed. Ways to reduce this residual dispersion were proposed and studied. In addition, the dispersion was measured using a scintillator screen in the dispersive section and used to extract the beam energy distribution.

8 Acknowledgements

To my supervisor Vladyslav Libov, I am really grateful for the opportunity to work here and to be a part of FLA community. Thanks for the guidance during my work and kind help in every work/life related question i had. It was nice to meet you!

To Vladymir Aushev for encouraging to participate in the summer student program and for a kind support during my time being a student.

To Olaf Behnke and the all organization team. Thanks for all effort you did!

Special thanks for Elena Mazzeo and Beatrice Jelmini for the great and fun summer. Thanks for the good company in the office, tea parties and sharing your life experience with me. Also thanks Elena for the most memorable apple trip I ever had. I will miss your company!

To all summer students! You were truly as a family for me during the stay. Especially thanks to Toni Bertólez and everybody who was organizing entertainments or was baking incredible cakes/pies/crumbles during the stay, you are the best guys! Thanks for the all memories I received during the summer!

To my mom and dad for their care and kindness and for who I am now.

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