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Abstract

The Accelerator Test Facility 2 (ATF2) commissioning group aims to demonstrate the feasibility of the Beam Delivery System (BDS) of the next linear colliders (ILC and CLIC) as well as to define and to test the tunning methods. As the design vertical beam sizes of the linear colliders are about few nanometers, the stability of the trajectory as well as the control of the aberrations are very critical.
The magnet displacements induced by ground motion are large enough for CLIC to perturb the beam stability above requirements. It is planned to measure the displacement of the magnets and implement a feed-forward correcting the effects on the beam trajectory with correctors (dipoles).
This article studies the possibility to detect ground motion effects on the beam trajectory at ATF2. Characteristics of the ground motion at ATF2 are presented, the effects of the magnet displacements on the beam trajectory are simulated and an algorithm predicting the induced trajectory fluctuations is evaluated. After the estimated ground motion effect has been subtracted from the BPM measurements, effect of the incoming beam jitter on the trajectory is reconstructed from these BPM measurements. The residual are compared as a function of the number of motion sensors used.

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The Accelerator Test Facility 2 (ATF2 [1]) commissioning group aims to demonstrate the feasibility of the Beam Delivery System (BDS) of the next linear colliders (ILC [2] and CLIC [3]) as well as to define and to test the tunning methods. As the design vertical beam sizes of the linear colliders are about few nanometers, the stability of the trajectory as well as the control of the aberrations are very critical.

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INTRODUCTION

The Accelerator Test Facility (ATF) successfully creates beam with almost the emittances required by the ILC [4]. The ATF2 facility [1] uses the beam extracted from the ATF damping ring. It was built to demonstrate the feasibility of the Beam Delivery System of a future linear collider, to implement and test the instrumentation and tunning procedures involved to obtain the nanometer scale transverse beam size necessary for a high luminosity. ATF2 is a follow-up of the Final Focus Test Beam (FFTB) experiment at SLAC [5]. ATF2 final focus optics are scaled-down from the ILC design and this is the first implementation of the local chromaticity correction scheme [6] (also used for the CLIC design).

In the final focus section (see figure 1), the large β functions magnify incoming beam jitter up to several microns displacement. Thanks to precise cavity BPMs [7][8] (with sub-micrometer resolution), it is possible to reconstruct the beam trajectory fluctuation pulse to pulse with a sub-micrometer resolution.

As the effect of the magnets vibrations on the pulse to pulse trajectory variations are of $1-6$ μm in the FF, these trajectory variations are measurable.

This paper describes the algorithm predicting the pulse to pulse trajectory fluctuations as a function of the magnet displacement measurements and show expected results as a function of the number of sensors needed.

After a brief description of the ATF2 ground motion, a method to select the best elements where the vibration sensors has to be placed is presented. The last sections describe a method to predict the trajectory fluctuations from theses sensor measurements and how to remove incoming beam jitter effects.

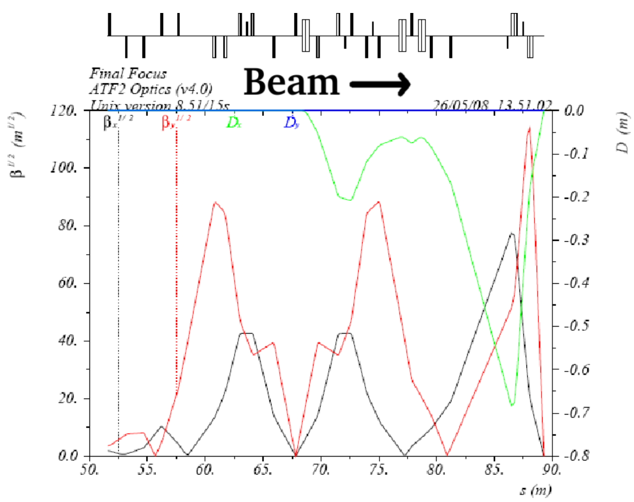

Figure 1: Nominal ATF2 final focus optics.

GROUND MOTION AT ATF2

The ATF2 ground motion has been measured in the end of 2008 and the parameters of propagating waves model has been fitted according to these measurements [9].

The Power Spectrum Density (PSD) measurement of the absolute ground motion is presented figure 2 and the coherence of the relative motion between two points for different distances between them are shown figure 3. These figures also compare the measurements to the prediction of the fitted model. As ATF2 is about 90 m long, frequencies below 1 Hz has no effect on the trajectory, due to a coherence of 1 between all the elements (they move altogether). The model is in good agreement with the measurements.

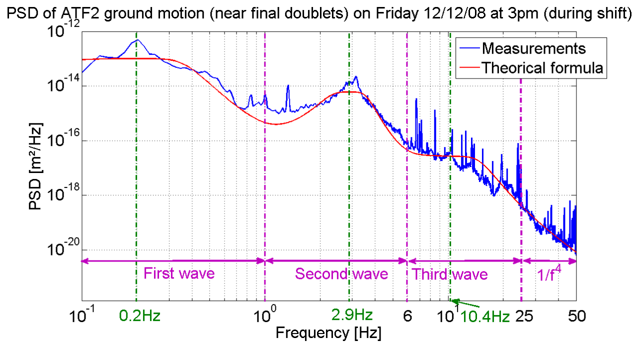

Figure 2: Power Spectrum Density of the Ground Motion measured at ATF2 and model results [9].

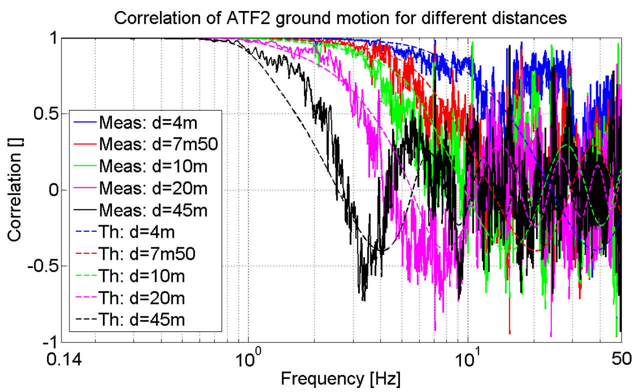

Figure 3: Coherence between 2 points for different distances for the Ground Motion measured at ATF2 and model results [9].

DETERMINATION OF THE SENSOR POSITIONS

Quadrupole displacements deflect the beam trajectory proportionally to its integrated strength KL and to the displacement $\delta X(quad)$ or $\delta Y(quad)$:

$$\begin{aligned} \Delta X'(quad) &= KL \times \delta X(quad) \\ \Delta Y'(quad) &= KL \times \delta Y(quad) \end{aligned} \quad (1)$$

The trajectory displacement at a BPM i (noted ΔX_i and ΔY_i) induced by this kick is described by the transfer matrix between the displaced quadrupole and that BPM $R(quad \rightarrow BPM_i)$:

$$\begin{aligned} \Delta X_i &= R_{12}(quad \rightarrow BPM_i) \times \Delta X'(quad) \\ &= R_{12}(quad \rightarrow BPM_i) \times KL \times \delta X(quad) \\ \Delta Y_i &= R_{34}(quad \rightarrow BPM_i) \times \Delta Y'(quad) \\ &= R_{34}(quad \rightarrow BPM_i) \times KL \times \delta Y(quad) \end{aligned} \quad (2)$$

In an ideal case, one would like to be able to measure the variation of position of all the quadrupoles and sum the effect for each BPM to get an estimation of the trajectory variation. However, the number of sensor is limited, and so their emplacements must be optimized to obtain the best results. To do so, the measured displacement of the beam at a BPM normalized by the displacement of the quadrupole ($\frac{\Delta X_i}{\delta X(quad)}$) has been computed for all BPMs and quadrupoles. The results are shown figure 4

The elements where the sum of the absolute value of this influence on all the BPMs (in vertical and horizontal plane) is the highest will be chosen to have sensors on them (as well as the first and last elements to simplify the estimation of all element positions). For the case with 20 sensors, these elements with sensors are indicated by a dashed gray line in figure 4.

One can see that the highest influence is obtained for elements in the extraction line and BPMs in the Final Focus. That is due to the large magnification between these two sections.

ESTIMATION OF THE TRAJECTORY FLUCTUATIONS DRIVEN BY GROUND MOTION

Element Vibrations from Measurements

To take the effects of the vibrations of the quadrupoles without sensor into account, their positions must be estimated. The estimation of the displacement δX_{est} of a quadrupole at a longitudinal position s_{est} is done linearly with the distance between the two closest quadrupoles with a sensor surrounding it (with measured displacement δX_{down} and δX_{up} and positions s_{down} and s_{up} respectively for the quadrupole downstream and the one upstream).

$$\delta X_{est} = \frac{s_{down} - s_{est}}{s_{down} - s_{up}} \delta X_{up} + \frac{s_{est} - s_{up}}{s_{down} - s_{up}} \delta X_{down} \quad (3)$$

The ground motion model has been used to generate the positions of all the elements for 100 pulses at 6 Hz. Using only the displacements of the quadrupoles with sensors selected according to the last section, the position of all the other elements has been estimated using equation 3.

The measurement of the quadrupoles motion takes into account the transfer function of ground motion sensors considered (geophones). These transfer functions are shown figure 5.

The amplitude of the displacements relative to the first element compared to the error introduced by the estimation for all the elements using 30 sensors is shown figure 6. The elements with sensors are again indicated with a dashed gray line. These errors are shown for 3 cases :

- using the real positions of the quadrupoles (plain line).
- using the measured positions which takes into account the transfer functions of the geophones (crosses).
- using the corrected measured positions where the amplitude is corrected dividing the Fourier transform of the measurements by the real part of the geophones transfer functions (circles).

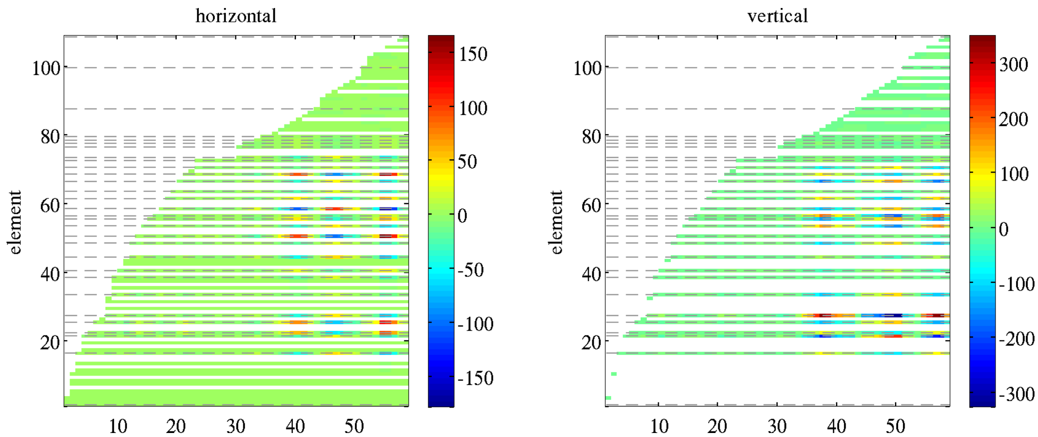

Figure 4: Influence of the displacement of all elements on all BPM readings.

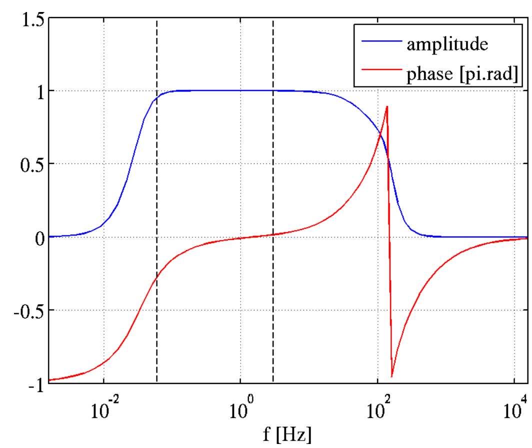

Figure 5: Transfer functions (amplitude and phase) of the geophone sensors.

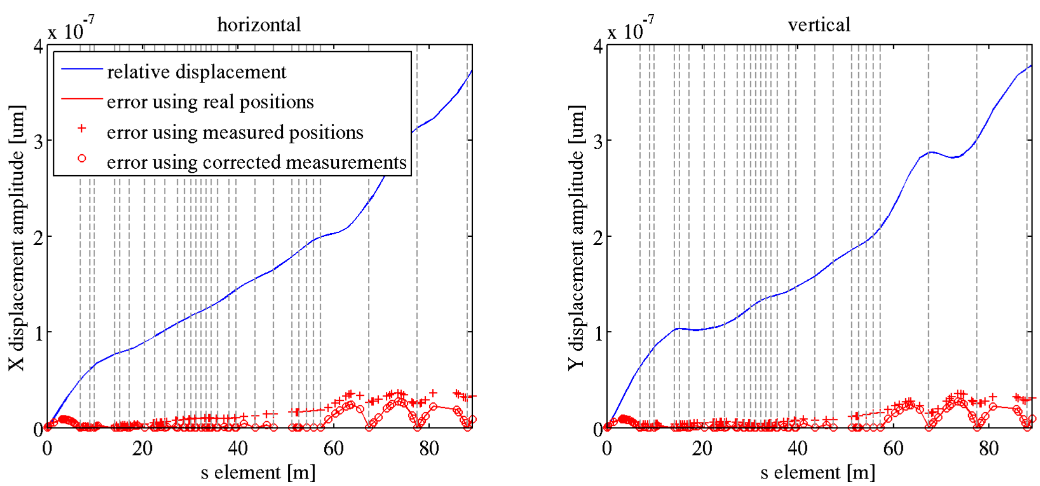

Figure 6: Amplitude of pulse to pulse element displacements and error on the estimation of these displacements using 30 sensors.

As most of the sensors are located in the extraction line, the error on the element displacements introduced by the linear estimation are small in that area ($\simeq 10nm$). On the other hand, despite there is only few sensors at in the final focus, the error is about $20nm$, demonstrating the validity of the linear estimation. Also the amplitude correction of the geophones' measurements improves the results significantly.

Estimation of Trajectory Fluctuations

As we have now an estimation of all elements displacements along the line, we can compute ΔX the trajectory fluctuation a BPM summing the influences of all the element displacements δX_i obtained from equation 2:

$$\begin{aligned} \Delta X &= \textstyle\sum_i R_{12}(elem_i \to BPM) \times K_i L_i \times \delta X_i \\ \Delta Y &= \textstyle\sum_i R_{34}(elem_i \to BPM) \times K_i L_i \times \delta Y_i \end{aligned} \tag{4}$$

The trajectory fluctuations are computed with the tracking code PLACET using the displacements of all the elements given by the model. The amplitude of the pulse to pulse BPM readings is shown in blue figure 7. The difference between the estimation of the trajectory variation and its simulation is shown in red for 3 cases :

- using 15 vibration sensors.
- using 20 vibration sensors.
- using 30 vibration sensors.

On can see that the error in the case of 30 sensors is as low as 100 nm which is significantly smaller than the amplitude of the trajectory variations induced by the ground motion ($1-5\mu$m).

RECONSTRUCTION OF THE TRAJECTORY FLUCTUATIONS DRIVEN BY INCOMING BEAM JITTER

It is absolutely necessary to correct for beam jitter effect as it is about 100 times higher the the ground motion effect accordingly to latest available measurements (see figure 8).

Once the effect of the ground motion has been removed from the trajectory fluctuations, only effect of the incoming beam jitter remains. As in ATF2 (and in linear colliders BDS in general) the longitudinal position has no influence on transverse position, the corrected BPM readings are then function of only fives parameters (X, X', Y, Y' and $\frac{\Delta E}{E}$). These parameters can be determined for any position of the linac, but as we want to determine the incoming beam jitter, the injection point has been chosen.

These parameters are obtained from the BPM readings using the transfer matrices from the injection point to each BPMs. From the transfer matrices definition we have :

$$B = M \times P$$

with :

$$B = \begin{pmatrix} X_{BPM_1} \\ \vdots \\ X_{BPM_n} \\ Y_{BPM_1} \\ \vdots \\ Y_{BPM_n} \end{pmatrix} \qquad P = \begin{pmatrix} X \\ X' \\ Y \\ Y' \\ \frac{\Delta E}{E} \end{pmatrix}_{inj}$$

$$M = \begin{pmatrix} R_{11}(inj \to BPM_1) \ldots R_{16}(inj \to BPM_1) \\ \vdots \\ R_{11}(inj \to BPM_n) \ldots R_{16}(inj \to BPM_n) \\ R_{31}(inj \to BPM_1) \ldots R_{36}(inj \to BPM_1) \\ \vdots \\ R_{31}(inj \to BPM_n) \ldots R_{36}(inj \to BPM_n) \end{pmatrix}$$

so the parameter are obtained with :

$$P = M^{-1} \times B \tag{5}$$

where M^{-1} is the pseudo inverse of M.

The effect on the trajectory of the incoming beam jitter obtain from equation 5 is $M \times P$, so the residuals are obtained with $B - M \times M^{-1} \times B$.

The spread of this residual over 100 pulses has been simulated for 4 cases:

- without previous subtraction of the effect of ground motion
- with previous subtraction of the effect of ground motion determined with 15, 20 and 30 sensors.

BPMs' noise and ground motion sensor transfer functions has been included in all the cases.

The results are shown figure 9. One can see the spread of the residuals decrease with the number of sensor used and accordingly to the results shown figure 7, no improvement is obtained with 15 sensors in the horizontal plane.

CONCLUSION AND PROSPECTS

We saw how to estimate the pulse to pulse beam trajectory fluctuations from the measurements of the vibrations of a limited set of magnets, with a criteria to select where to put the sensors. Despite the incoming beam jitter has an effect 100 times lager, it has been shown effect of the ground motion can still be detected with the presently available BPMs at ATF2 with 20 ground motion sensors.

However the criteria to select where to put the sensors which was used was not optimal, further study could reduce the number needed. Also, only the detection of the ground motion effect on the trajectory has been studied but the feed forward itself has not yet been considered. As the incoming beam jitter has effect 100 times larger than the ground motion one, to be have a measurable impact for ATF2, a feed-forward would require to lower the incoming beam jitter with a new extraction kicker system or using a dedicated feedback.

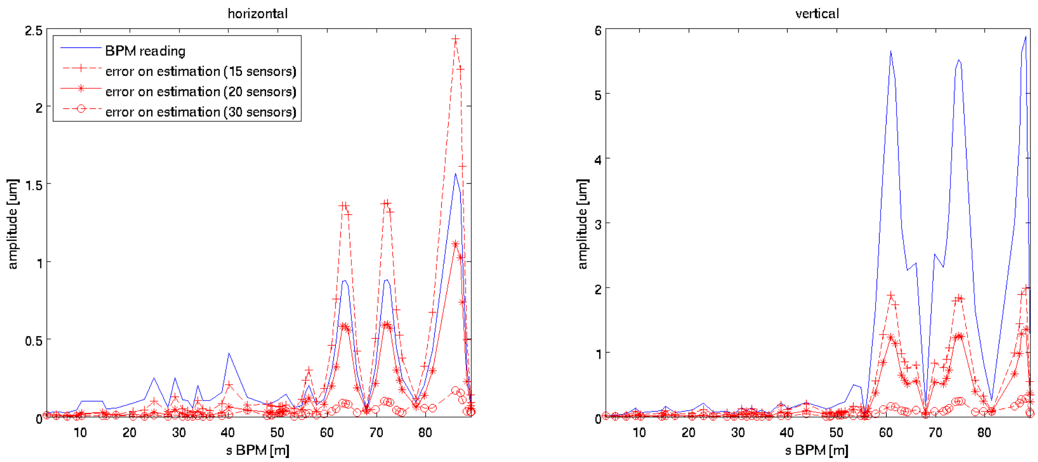

Figure 7: Amplitude of the pulse to pulse trajectory variations at 6 Hz and error on the estimation of these variations using 15, 20 or 30 sensors.

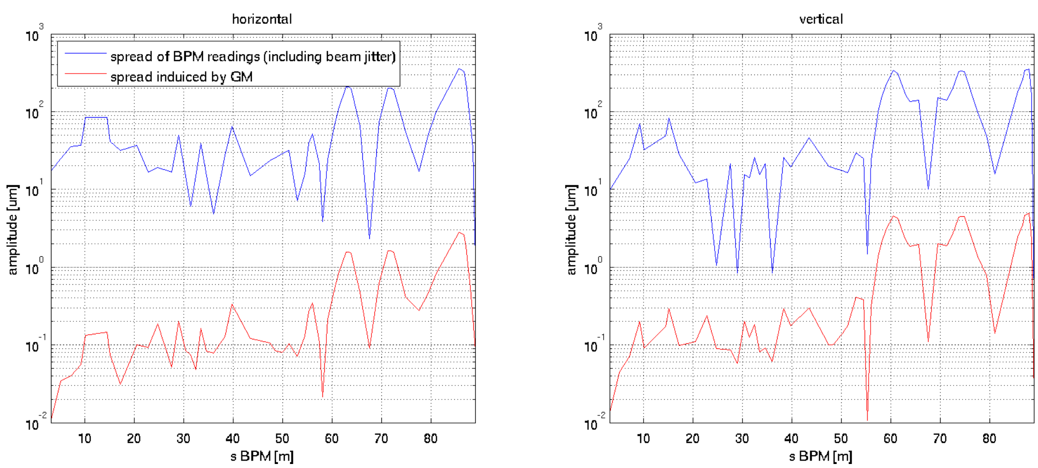

Figure 8: Comparison of the beam jitter amplitude induced by the incoming beam jitter and by the ground motion.

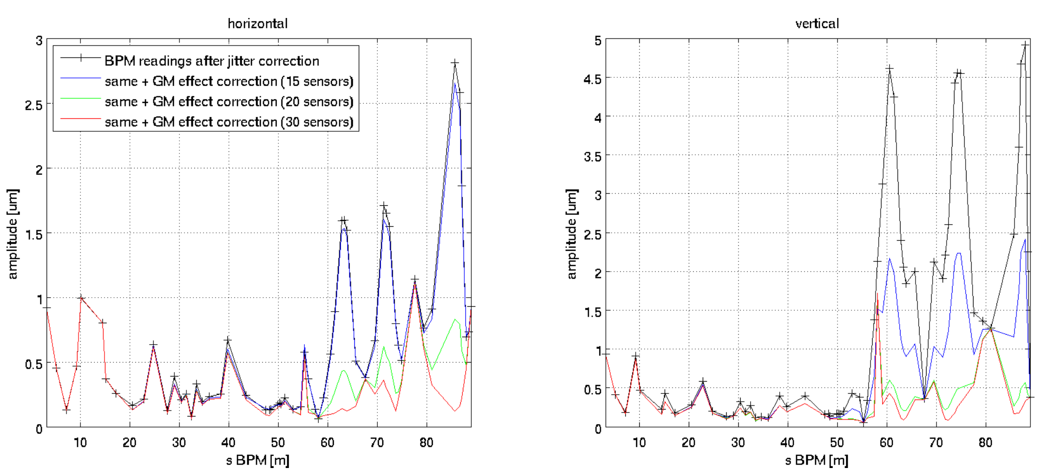

Figure 9: Comparison of the residual of BPM readings corrected by ground motion effect and incoming beam jitter as a function of the number of sensors used.

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