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Report on wakefield free steering performance to mitigate wakefields.

Executive summary:

The CERN and KEK teams have performed a detailed analytical and numerical study of the wakefield impact on the beam orbit and size at ATF2. These studies have been benchmarked and compared with orbit measurements performed during different experimental campaigns in May and December 2017. This report will focus on the wakefield impact on the beam orbit.

1. INTRODUCTION

Intensity-dependent effects on the beam size at the ATF2 IP have been consistently reported, showing a degradation of the beam size, as measured by the IPBSM, that is compatible with the effect imparted by wakefields [1]. Figure 1 shows IPBSM modulation as a function of the beam intensity.

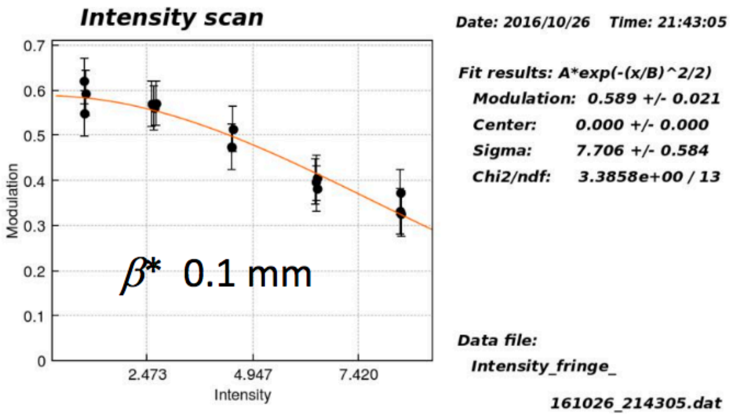

Fig. 1: IPBSM modulation as a function of the beam intensity. Smaller modulation indicates an increased beam size.

The intensity dependence problem due to wakefields has been addressed all along the ATF2 operation during the last years, and extensive studies have been performed within WP2, including wakefields modelling, tracking simulations, and measurements. A particular effort has been made in 2016 in order to solve this problem, and a dedicated "wakefield measurement campaign" took place during the November-December 2016 operation [2,3]. On this occasion, several beam line components, identified as important wakefield sources, have been removed from the beam line. Figure 2 highlights the identifiers and the location of the components removed. They were all BPMs.

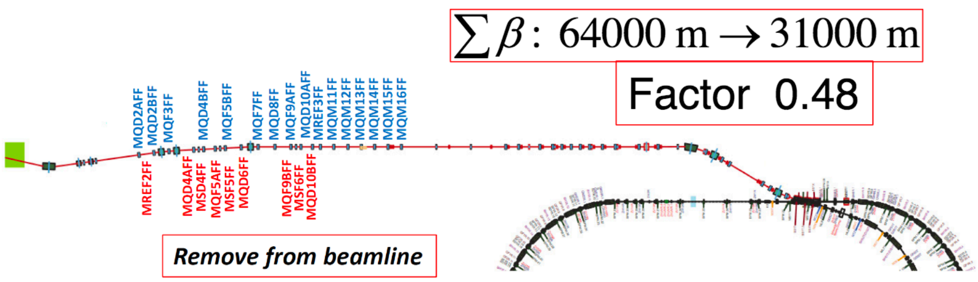

Fig. 2: In red, the identifiers of all BPMs that were removed from the beam line in 2016.

2. WAKEFIELD-FREE STEERING

The wakefields being a collective effect that occurs within the bunch, the impact of wakefields normally affects the beam size rather than the orbit itself. In case of very strong wakefields kicks, though, the effect of the wakefields can be so strong to deflect the centroid of the bunch itself, effectively distorting the orbit. Whenever an effect is measureable from the orbit, this effect can be mitigated using beam-based techniques that rely on orbit measurements. One such technique is wakefield-free steering (WFS), an orbit correction method which extends the well-known dispersion-free steering (DFS) to correcting not just unwanted dispersion but also wakefield effects.

The functioning of WFS can be understood considering the set of equations that define it:

$$\begin{pmatrix} & & \mathbf{y}-\mathbf{y}_0 \\ \omega_{\mathrm{DFS}} & \cdot & (\boldsymbol{\eta}-\boldsymbol{\eta}_0) \\ \omega_{\mathrm{WFS}} & \cdot & (\mathbf{y}_{\mathrm{w}}-\mathbf{y}_0) \\ & & 0 \end{pmatrix} = \begin{pmatrix} & & \mathbf{R} \\ \omega_{\mathrm{DFS}} & \cdot & \mathbf{D} \\ \omega_{\mathrm{WFS}} & \cdot & \mathbf{W} \\ \beta & \cdot & \mathbf{I} \end{pmatrix} \begin{pmatrix} \theta_1 \\ \vdots \\ \theta_m \end{pmatrix},$$

where **R**, **D,** and **W** are, respectively, the orbit, the dispersion and the wakefield response matrices. **I** is the identity matrix, θ is the vector of corrector strengths, i.e. the unknowns of the system. On the left-hand side $\mathbf{y}$, $\mathbf{y}_0$, $\mathbf{y}_w$, $\boldsymbol{\eta}$, and $\boldsymbol{\eta}_0$ are the observables: $\mathbf{y}_0$, is the initial orbit, $\mathbf{y}$ is the vector of measured BPM readings for the beam in nominal conditions; $\mathbf{y}_w$ is the vector of BPM readings for the beam with different charge; $\boldsymbol{\eta}$ and $\boldsymbol{\eta}_0$ are the measured and the target dispersion, respectively. The other parameters ω_{DFS}, ω_{WFS}, and β are free and need to be tuned to achieve best performance. More details on DFS and WFS can be found e.g. in Ref. [4].

The above system of equations is typically over-determined, so its solution must be computed in a least-squares sense. From a physical viewpoint, the solution to this system of equations corresponds to finding the correctors setup that best satisfy the following conditions, simultaneously:

1. the measured dispersion $\boldsymbol{\eta}$ matches the nominal dispersion $\boldsymbol{\eta}_0$;
2. the wakefield orbit $\mathbf{y}_w$ is not far from the initial orbit $\mathbf{y}_0$;
3. the nominal orbit is not far from the initial orbit $\mathbf{y}_0$.

The last condition is needed to guarantee beam stability and to reduce beam losses during the application of WFS.

3. EXPERIMENTAL VERIFICATION OF DFS AT ATF2

DFS was successfully applied to ATF2 in the past [5], showing good performance as visible in Fig. 3. At that time the tests were limited to the extraction line, that is, the linear part of the lattice, and the final focus was excluded. WFS was also applied, but a significant effect could be seen only when purposely misaligning the reference cavity, which is a known significant source of wakefields.

A dedicated study of WFS in the whole ATF2 line, including the final focus, has been initiated this year within the framework of a doctoral thesis devoted to study (and possibly help mitigate) the intensity dependent effects at ATF2.

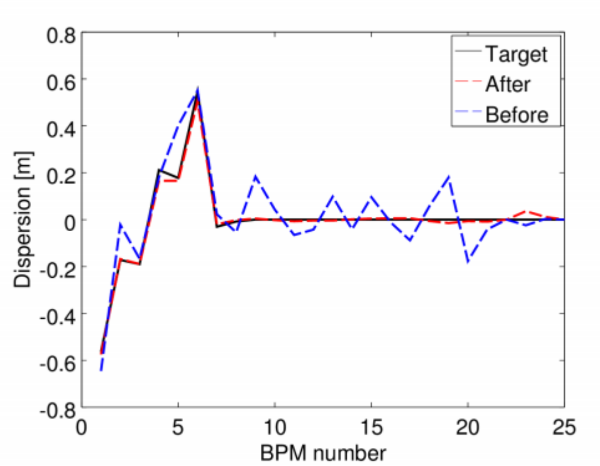

Fig. 3: Horizontal dispersion before and after the application of DFS at ATF2.

4. SIMULATION OF INTENSITY-DEPENDENT EFFECTS ON THE ORBIT

PLACET simulations were performed to confirm and assess the impact of the beam line components removal on the ATF2 performance, see Fig. 4. Also, the impact of an initial position and angle jitter on the orbit was studied, and its amplification through wakefield effects. Figure 5 shows the standard deviation of the BPM readings along the ATF2 line under the effect of jitter, for several random seeds. A dependence on the beam charge is clearly visible.

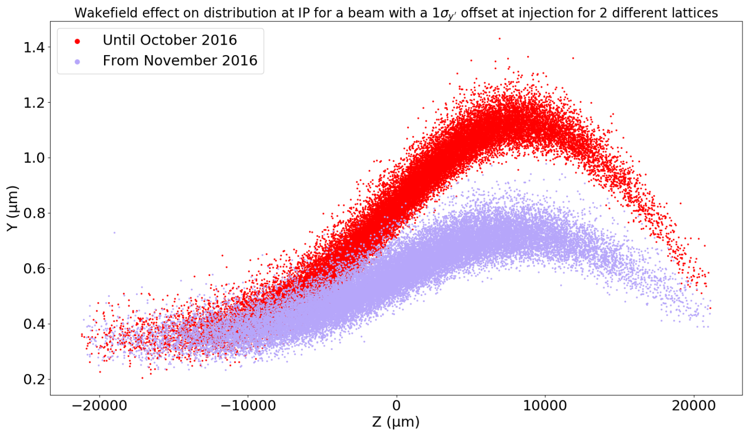

Fig. 4: Effect of wakefields on the beam distribution at the IP, for a beam with an initial angular offset of 1$\sigma_{y'}$*, comparing the lattice before and after the removal of some beam line components in November 2016.*

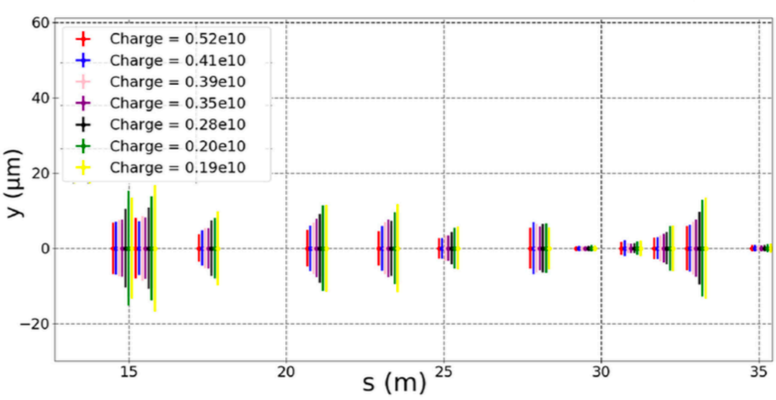

Figure 5: Measurements of mean orbit and standard deviation along the line at BPMs for 7 different charges between s = 12 m and s = 35 m.

5. MEASUREMENT OF INTENSITY-DEPENDENT EFFECTS ON THE ORBIT

A campaign of measurements was conducted in May 2017, and later also in November 2017, aimed at reproducing the effects observed in simulation. Several measurements were performed at different beam intensities, and a sophisticated data analysis procedure involving the use of the singular-value decomposition (SVD) was put in place [6]. The beam charge was ramped from 0.3 nC per bunch to 0.83, in 7 steps; 100 different orbits were acquired for each step to improve statistics.

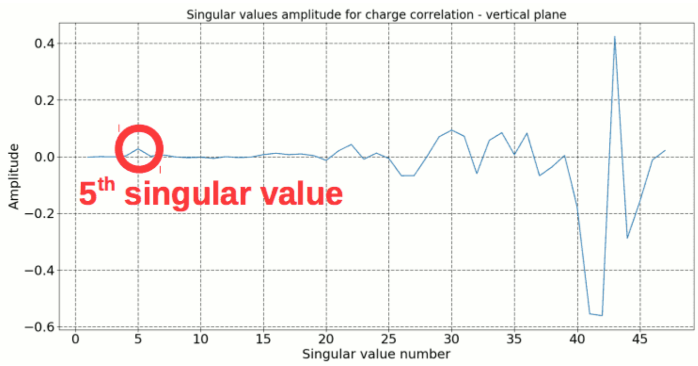

Figure 6: Charge correlation of each singular value. The 5th singular value stands out among the smallest ones. Singular values above 10 are normally associated with noise and carry little information.

The SVD technique was used to identify local and global correlations between BPM readings and charge measurements, see Fig. 6. By looking at the singular vectors calculated using SVD that show an intensity dependence, it was possible to identify four BPMs showing a particularly pronounced response to the beam charge. Figure 7 shows a global view on all BPMs, as a function of the charge variation (identified by the pulse number). The 'Vertical orbit' axis shows the component of the orbit identified by the SVD as solely dependent on the charge. It emerges that over the full charge scan the orbit measured by some BPMs changes over a range of about 60 micrometers. The ratio of orbit distortion with the beam charge was evaluated to be up to 97 µm/nC. The reasons for such a correlation are being investigated. Obvious hardware-related reasons have been examined, and no obvious one was found. Physical reasons due to wakefield effects are being investigated through data analysis and numerical simulations.

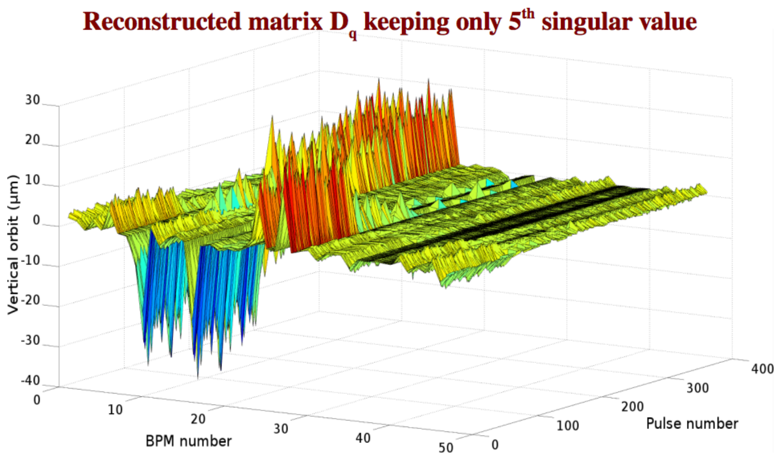

Figure 7: Response of all BPMs measurement to beam charge changes. The bunch charge grows with the pulse number.

6. FUTURE DEVELOPMENTS

The on-going effort in modelling, measuring and mitigating the wakefield sources in ATF2 provides invaluable knowhow and experience in preparation for similar work at future linear colliders. The next steps will include detailed analyses of the data acquired in November 2017, using SVD, the experimental test of WFS (March 2018?), and the definition and the assessment of potential wakefields mitigation techniques. Based on the results, a detailed study of the ILC scaling and implications will be performed.

7. REFERENCES

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