ORBIT ANALYSIS AT THE TTF LINAC USING MODEL INDEPENDENT METHODS

P. Castro, C. Lackas, M. Seidel, M. Wendt, DESY, Germany

Abstract

Model independent analysis (MIA) [1] can be used in accelerators to analyze large statistical samples of orbit data. The basic principle consists in identifying correlated beam motion at the different BPM's by a singular value decomposition of a BPM matrix that contains consecutively measured orbit vectors. The number of significant singular values equals the number of independently jittering variables in the system, eg. beam energy, offset and angle. The remaining values are a measure of uncorrelated noise, for example caused by the BPM electronics. We discuss the application of MIA to the TTF linac in view of jitter analysis, residual dispersion, monitor resolution.

1 PRINCIPLES OF MODEL INDEPENDENT ANALYSIS

The idea of Model Independent Analysis (MIA) [1] is to analyze large statistical samples, for example of beam orbit data that contains "natural" orbit jitter, to unveil correlations between the measurements at the individual observation points and to understand the underlying physical processes. For the statistical analysis no model of the accelerator is needed. We give here examples for the application of MIA to the TTF accelerator - the determination of the monitor resolution, measurement of residual dispersion in the undulator region and identification of erroneous BPM's.

In order to perform model independent analysis a large set of BPM data vectors $\hat{\vec{b}}_p$ for each measured pulse p is needed. The average orbit is subtracted and the individual vectors are normalized by the square root of $M \cdot P$, the number of BPM's and pulses respectively:

$$\vec{b}_p = (\hat{\vec{b}}_p - <\hat{\vec{b}}>)/\sqrt{PM}. \qquad (1)$$

These normalized difference vectors are arranged rowwise in an orbit matrix $\mathbf{B}$ that contains finally P rows, and M columns. Typically the number of pulses is much larger than the number of BPM's.

Next the matrix $\mathbf{B}$ is decomposed into a product of three matrices using singular value decomposition (SVD). The left and right matrices are orthogonal, whereas the one in the middle is diagonal and contains the singular values. It turns out that the column vectors of the matrix $\mathbf{V}$ point into the direction of linear independent modes of orbit jitter. They are called spatial vectors and are orthogonal to each other. Their length is normalized to 1. The M dimensional vector space is spanned by the BPM's. Typical patterns are betatron oscillations or patterns proportional to the dispersion function, caused by energy jitter.

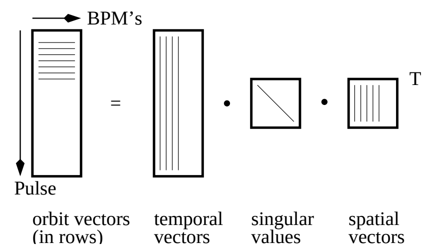

Figure 1: Schematic singular value decomposition of a BPM matrix (left).

The column vectors of $\mathbf{U}$ describe the time development of the corresponding orbit patterns in $\mathbf{V}$ and are called temporal vectors. The singular values in $\mathbf{\Lambda}$ are given by the rms jitter amplitudes averaged over space (BPM's) and time (pulses) for the individual jitter modes. The vectors with the largest corresponding singular values contain the prominent jitter modes. Numerical algorithms for the computation of singular value decompositions commonly sort their output for descending eigenvalues [2]. The SVD of a BPM matrix is shown schematically in Fig. 1.

$$\begin{aligned} \mathbf{B} &= \mathbf{U} \cdot \mathbf{\Lambda} \cdot \mathbf{V^T} \\ \text{with}: \quad \mathbf{U^T U} &= \mathbf{1} \\ \mathbf{V^T V} &= \mathbf{1} \\ \text{and} \quad \mathbf{\Lambda} &= \begin{bmatrix} \lambda_1 & 0 & . \\ 0 & \lambda_2 & . \\ . & . & \lambda_m \end{bmatrix} \end{aligned} \qquad (2)$$

2 LAYOUT OF THE ACCELERATOR

The Tesla Test Facility (TTF) [3][4] is presently used to drive a SASE FEL. A schematic layout of the TTF linac is given in Fig. 2. After bunch compression and acceleration to 240 MeV the beam is passing an undulator section where the laser radiation at typical wavelengths of 100 nm is produced.

The undulator section consists of three modules 4.5 m long. Each module has an integrated F0D0 structure of 5 cells providing a phase advance of approximately 270°. In total 30 BPM's are installed in the undulator section, that is, one per quadrupole. The BPM's of the undulator modules 1 and 2 are of the antenna type [5]. In undulator module 3

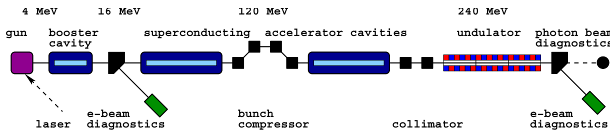

Figure 2: Schematic layout of the TTF accelerator.

there are 10 waveguide BPM's. The experimental section downstream the undulator includes three stripline BPM's and one of them is located downstream the spectrometer dipole. For the numerical examples presented in the next section we use only the 20 antenna BPM's in the modules 1 and 2, and one of the stripline BPM's in the dispersive region beyond the spectrometer dipole. Fig. 3) shows a cross section of the antenna BPM. Due to the space limitations the two pairs of opposing pickup electrodes had to be separated longitudinally by 41 mm = 3/2 undulator periods. The antennas are rotated by ± 30 deg with respect to the horizontal plane. The electronics is a broadband AM/PM "monopulse" system [6]. It outputs a beam intensity independent analog displacement signal for each passing bunch. The output signals are digitized with 14-bit VME AD converters.

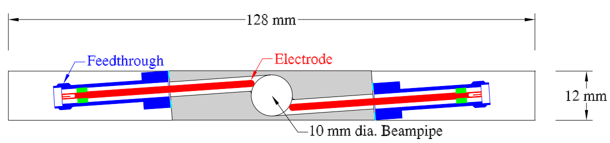

Figure 3: Schematic layout of the undulator BPM's.

3 GENERAL OBSERVATIONS AND SINGULAR VALUE SPECTRUM

As a typical example we show here a recording of about 600 beam pulses, measured at 19 well functioning BPM's. During the recording a steerer magnet was changed in steps to demonstrate the effect of orbit changes.

The singular value spectrum we obtain is shown in Fig. 4 and the first four spatial and temporal vectors in Figs. 5 and 6 respectively. The strongest mode in the first vector is caused by energy jitter. The amplitude of the first spatial vector is close to 1 at the last BPM, which sits in the spectrometer arm and is the only one with a nominally nonzero dispersion. The next largest singular value corresponds to the orbit variation caused by the steerer change. The corresponding temporal vector shows clearly the same time dependence as the steerer current, shown in Fig. 7. The third singular value could correspond to a betatron mode, orthogonal to the one caused by the steerer.

It is important to point out that the SVD produces *orthogonal orbit patterns* which are not necessarily connected to the underlying physical processes. In general each of the vectors is a linear combination of physical vectors. Often, however, one or two processes are dominating, and their temporal developments are distinct enough such that the SVD naturally separates them as in our example.

The singular value spectrum in the example shows about 5 significant values, whereas the remaining ones represent the uncorrelated noise produced by the BPM electronics. Erroneous BPM's can be identified if they show either too much noise (erratic readings) or unusual small noise (cable not connected or similar). In the first case the readings of the BPM are not correlated with other ones and the corresponding spatial vector would be 1 at the BPM and practically zero elsewhere. In the second case we would find a single unusually small singular value in the spectrum.

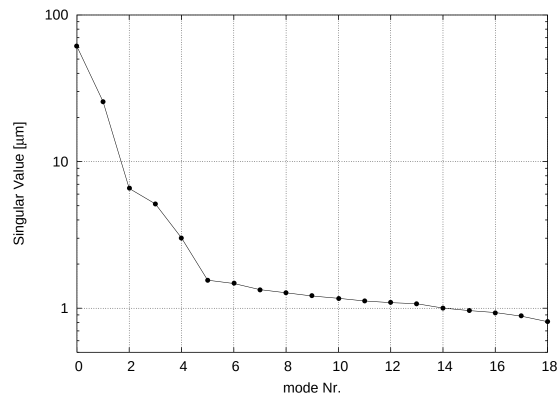

Figure 4: Singular value spectrum.

4 RESOLUTION OF THE BPM'S

As pointed out in the above section the tail of the singular value spectrum is a measure of the uncorrelated noise in the BPM readings and therefore a measure of the resolution. The noise amplitude can be extracted by quadratically summing up the insignificant singular values (noise floor):

$$\sigma_{\text{res}} = \left(\sum \lambda^2_{\text{insignfct}} \right)^{1/2} \qquad (3)$$

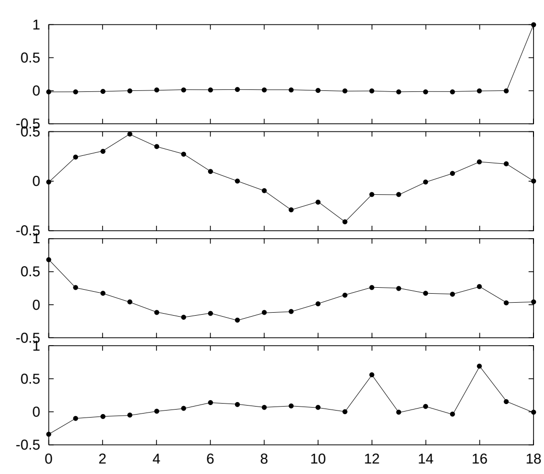

Figure 5: First four spatial vectors.

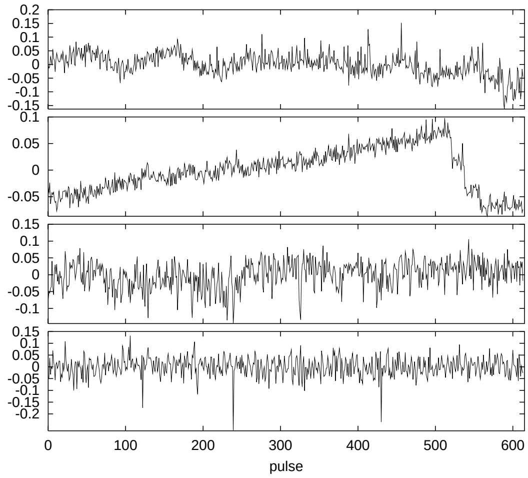

Figure 6: First four temporal vectors.

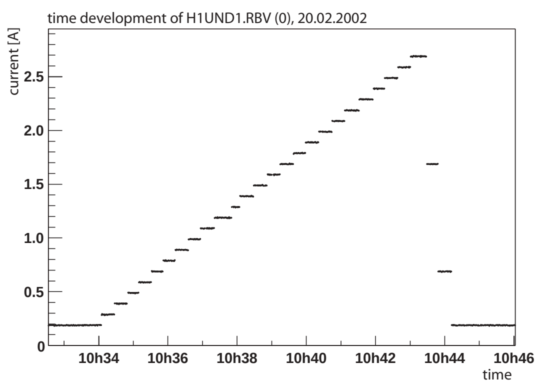

Figure 7: Current in a horizontal steerer magnet upstream of the undulator, as a function of time.

With a large data set one can also analyze the variation of the BPM resolution with the bunch charge by performing the SVD for different charge bins. This has been done for a data set of 800 pulses and the result is shown in Fig. 8. We observe an optimum range of bunch charges for the best resolution of the BPM's. Resolutions around 5 μm can be reached.

5 RESIDUAL DISPERSION IN THE UNDULATOR REGION

The dispersion in the undulator region should be as small as possible in order not to disturb the FEL operation. Using MIA we can observe the residual dispersion function by analyzing the spatial vector that represents the energy jitter. Normally this mode is by far the strongest jitter mode in TTF. It has the biggest amplitude at the BPM in the dispersive region beyond the spectrometer magnet. The SVD determines in principle the fraction of jitter at the other BPM's that is proportional to the jitter at the dispersive BPM. In this way it is possible to determine also very small values of dispersion in the undulator region, just by analyzing the orbit jitter. Fig. 9 shows the thereby determined residual dispersion within the undulator. It was obtained by scaling the corresponding spatial vector with the known dispersion function at the BPM in the spectrometer arm. The rms dispersion is about 10 mm. Using the known dispersion at the spectrometer BPM it is also possible to compute the energy jitter which amounts to $2.5 \cdot 10^{-4}$ in our example.

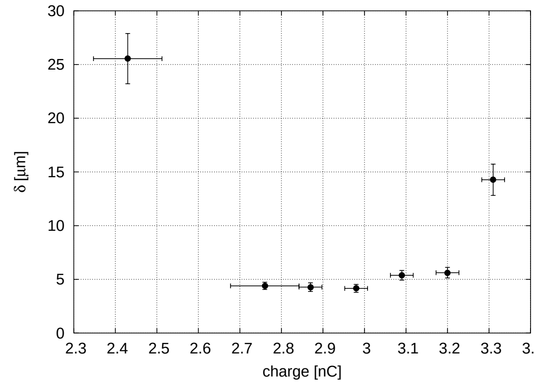

Figure 8: Resolution of the BPM's as a function of the bunch charge, obtained by performing the SVD on different charge bins.

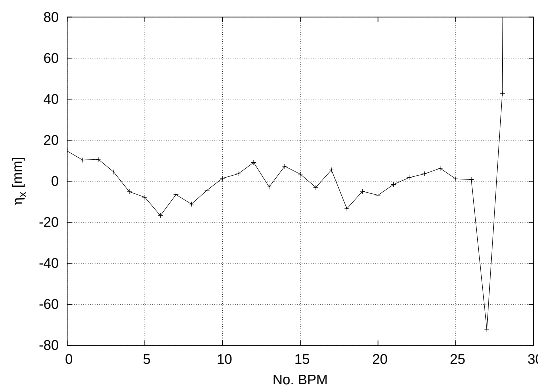

Figure 9: Residual dispersion function in the undulator. The BPM in the spectrometer arm, which is off scale, has about 1.5 m nominal dispersion.

6 REFERENCES

[1] J. Irwin *et al.*, "Model-independent beam dynamics analysis," Phys. Rev. Lett. **82**, 1684 (1999).

[2] W.H. Press et al., Numerical Recipes in C, Cambridge University Press (1992).

[3] D.A. Edwards (Ed.), TESLA Test Facility Linac - Design Report, TESLA 95-01 (1995).

[4] P. Castro, Performance of the TTF Linac, these proceedings.

[5] R. Lorenz et al, Beam Position Monitors inside the FEL Undulator of the TTF Linac, PAC 97, Vancouver.

[6] M. Wendt, BPM Read-out Electronics Bases on the Broadband AM/PM Normalisation Scheme; DIPAC 2001 Proceedings, ESRF, Grenoble, May 2001.