# CONSIDERATIONS ABOUT OPTICS-BASED PHASE-SPACE MEASUREMENTS AT LINAC-BASED FEL FACILITIES

Bolko Beutner*, Eduard Prat, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

*Abstract*

Transverse phase-space measurements are an essential aspect for FEL facilities. After acceleration in the injector the energy is sufficiently high to bring the beam out of the space-charge dominated regime, thus optics based techniques are favored. The beam moments at a given point in the machine are fitted to beam size values downstream with different phase advances between the reconstruction and the measurement point. Two key methods are possible. Beam sizes can be measured at different positions in the beam line keeping the lattice unchanged. The other possibility is to actively change quadrupoles and use only one screen. These two techniques are compared in this paper including Monte-Carlo studies on systematic errors using the SwissFEL Injector Test Facility as an example. Beam size measurements, for instance done with OTR screens as profile monitors at the SwissFEL Injector Test Facility, are critical for such measurements. The analysis of these images can be a challenge, especially if the signal-to-noise is compromised for example by low bunch charges. This study on the phase-space measurement techniques will be completed by a discussion of the image post-processing procedures.

## PHASE-SPACE MEASUREMENTS

Measurements of the phase-space distribution of high energy beams (above about 100 MeV) are typically done by measuring the beam profiles at different phase advances between a reconstruction point and one or more profile monitors. Then either a fit of the beam-moments to the spot sizes or tomographic methods are used to reconstruct the phase-space distribution (compare [1] and [2]). Apart from the image analysis of the acquired image the main practical question for these measurements is how the phase advance in the lattice is generated. Either a series of profile monitors is used at different positions in a well-defined lattice, i.e. a FODO channel. Or the beam profiles are measured at a single position for different phase advances between the measurement and reconstruction point generated by changing the optics. The latter method is used in conventional quadrupole scans. A more advanced method is a scan with multiple quadrupoles at the same time. A precalculated list of quadrupole settings provides an almost constant spot size for the various phase advances needed for the scan. Using this approach the typical diagnostics problems with strongly varying beam sizes and intensities, which typically occur in single quadrupole scans can be mitigated.

* bolko.beutner@psi.ch

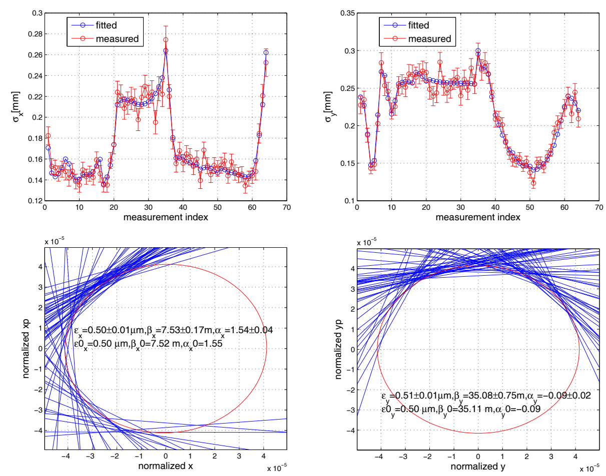


Figure 1: Example of a multi-knob scan at the SwissFEL 250 MeV Injector Test Facility. The upper plots show the beam size in x and y as a function of measurement index. Note that the first half of the scan steps providing the phase advance in x while the results for the y-plane is presented in the second half. In the lower plots the reconstructed normalized phase-space distribution is shown with the corresponding beam size lines. The presented data are simulations including an 10% measurement error in beam size.

Using different positions to measure beam profiles along the lattice is another common way to measure emittance. In principle any lattice is suitable for such kind of measurements as long as the total phase advance has sufficient coverage. In this paper we focus on measurements in a FODO channel. One advantage of this approach is the constant spot size. This relaxes the diagnostics requirements of dynamic range of beam size measurements. Another advantage of a FODO approach is the cancelation of energy errors up to first order when reconstructing the emittance(compare [1]).

In contrast to methods with a fixed lattice a set of different optics allows for a more compact diagnostic layout. Fig. 1 shows an exemplary measurement of such a scan. A table of precalculated settings for three upstream quadrupoles provides a phase advance of 170° while keeping the beta-function at the screen location between 10 and 30 m. If more quadrupoles are involved in the scan, the beta value can be kept constant. However for the sake of simplicity and without any significant loss in measurement precision, we utilize only 3 quads for the scan.

To evaluate the performance of the two discussed methods we need to evaluate how stable they are against mea-

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surement errors of the beam size, optics mismatch, or uncertainties in the knowledge of the transfer matrix, namely the quadrupole fields or beam energy.

We perform Monte-Carlo runs to estimate to estimate the systematic errors of the two different methods. Diagnostics setups designed for the SwissFEL Injector Test facility are used for this study [4][5]. A FODO layout with 7 half-cells of 22.5° phase advance each is compared with a multi-knob measurement optics set consisting of 16 steps of 10° phase advance covering a total of 160°.

In this study we assume a quadrupole field error and an energy error of 1%, and a relative beam size error of 10%. Each pixel in Fig. 2 and Fig. 3 indicates the relative average emittance error of 100 random seeds as a function of the incoming optics. In [2] a similar study for a FODO setup was presented. In the present study we are not analyzing individual error sources but the total effect of different contributions.

In the FODO setup the smallest error is about 6% while in the multi-knob setup an error as low as 3% is achievable. The main reason is the larger number of measurement points with finer resolution in phase advance. This is an advantage of the multi-knob methods since the phase resolution in a given FODO lattice is fixed. Additional FODO cells would improve the situation but other boundary conditions might not allow this.

In Tab. 1 we summarize the different aspects for the two methods. As we have seen in the previous section the total error sensitivity favors the multi-knob technique. Despite the advantages of the constant optics FODO method in terms of quadrupole field errors and hysteresis, and stability against energy error the higher number of measurement points in the multi-knob method makes this option favorable. Technical aspects such as magnet cycling or online energy measurement with high precision BPMs in dispersive sections render the advantages of the FODO even less critical.

A diagnostics channel requires a matching section to setup the incoming optics. In the FODO this is the periodic solution. In a multi-knob scan this working point is less constrained. In principle the optics sets for the multi-knob scan can be calculated for a wide range of optics. Therefore more possible locations for multi-knob measurement can be expected in the lattice.

A FODO setup requires a lot of space and diagnostics components while a multi-knob diagnostics setup allows a compact solution.

A constant multi-position measurement technique would allow for (semi-)parasitic measurements if i.e. wirescanners are used as profile monitors – this is not possible with a variable optics setup.

Since in a multi-knob measurement the relative phase advance between the horizontal and vertical plane can be chosen arbitrary it is possible to determine the four coupling terms of the beam $\langle xy\rangle$, $\langle xy'\rangle$, $\langle x'y'\rangle$ and $\langle x'y\rangle$. While in the FODO channel the phase advance in $x$ and $y$ is similar and not all coupling correlation can be measured.

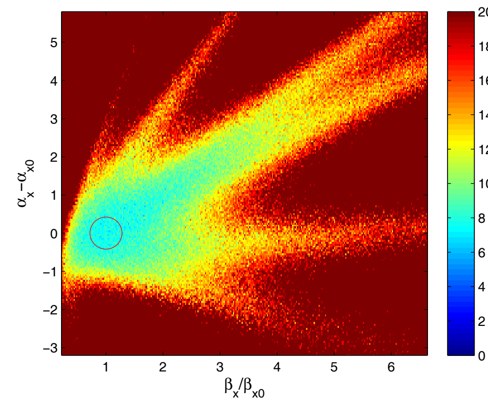


Figure 2: Relative emittance error (in percent) of an example FODO measurement setup for different incoming optics. The color code is limited to 20% to make the details around the matched solution visible. The periodic solution of the FODO lattice is indicated by the red circle ($\beta_{x0} = 2.26$ m $\alpha_{x0} = 0.697$). We assumed a quadrupole field error and an energy error of 1% and a relative beam size measurement error of 10%.

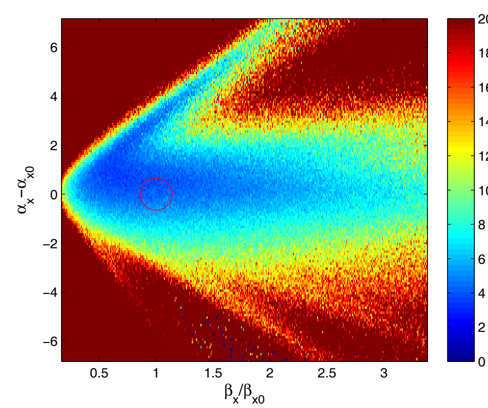


Figure 3: As in Fig. 2, but this figure represents a multi-knob measurement. The red circle represents in this case the incoming optics which was used as initial parameter for the calculation of the optics set ($\beta_{x0} = 29.57$ m $\alpha_{x0} = -0.1703$).

In conclusion if no phase-space measurements for high repetition rate is required, which would call for a parasitic operation mode, our data strongly favor a multi-knob measurement setup.

## IMAGE ANALYSIS

Image analysis in context of emittance measurements have been discussed earlier (e.g. [1], [2]), [3]. Here we discuss improvements in our image processing procedure with respect to an earlier discussion.

Our main goal for the image processing is to separate from background those parts of the image, which are beam related, to allow for RMS beam size calculations free of



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Table 1: A Summary of Different Aspects of Comparison between the Different Methods

| | FODO | Multi-Knob |
|---|---|---|
| **Errors Sensitivity** | worse | better |
| **Optics Integration** | required | not needed |
| **Availability** | only in FODO | everywhere with 3-4 quadrupoles |
| **Number of elements** | several quadrupoles and screens | 3-4 quadrupoles and a screen |
| **Required space** | more | less |
| **Parasitic operation** | yes | no |
| **Coupling Studies** | not possible | possible |

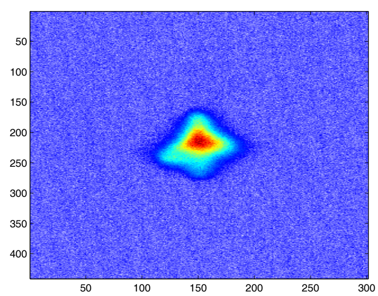


Figure 4: An example beam image obtained from an OTR system at the 250 MeV SwissFEL Injector Test Facility.

noise contributions.

This is achieved by an intermediate smoothing of the image and then a comparison with a certain threshold. Pixels above the threshold in the smeared out image are considered to be beam related, all others not. After this selection the smoothed image is not used any further. The original image is masked with this selected region. Using these beam related pixels for RMS beam size calculations stabilizes the whole process since noise in the background does not contribute anymore.

The scheme only gives reasonable results if the threshold value is determined appropiately. A good value can be found by an evaluation of the RMS beam size as a function of the threshold parameter. In many cases the beam size is almost constant within some interval of the threshold parameter. Since our interest is mainly the beam size a threshold value from this interval is a good choice.

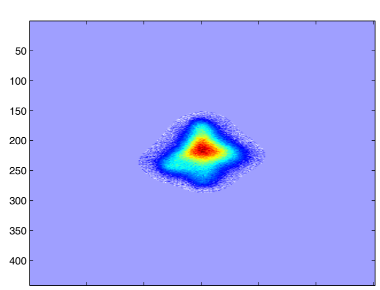


Figure 5: The same image as in Fig. 4 after post processing.

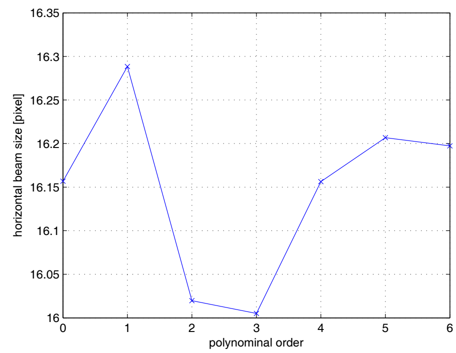


Figure 6: RMS size as function of offset order. The beam spot image from the previous figures was used.

An example of such a post processing is shown in Fig. 4 and Fig. 5.

Unfortunately this simple selection of the threshold is not always possible. One reason is given by correlations in the residual background after background image subtraction. In other words the offset of the image is not constant over the image. Such correlations give rise to asymmetries in the selected regions. As a result the beam size remains dependent on the threshold parameter, which makes it difficult to select a proper value of the threshold (compare Fig. 2 from [2]).

### *Image Offset*

In the present version of our image analysis software a 2D-polynomial is fitted to the residual image and subtracted. To avoid contributions from the beam the margin of the image of typically one tenth of the image size is used for this fit.

In practice polynomial orders of 2 and 3 are best suited. Higher orders can create artifacts which spoil the whole beam size determination. A typical example is in Fig. 6.

### *Threshold Determination*

Evaluation of a curve RMS beam size versus threshold parameter can be used to determine the threshold parameter. Since neither the relevant range of the threshold parameter nor the required resolution granularity of such a scan are known we decided to use an iterative procedure.

Starting from the maximum threshold value (the whole image is below this threshold) the value is reduced step by step. First we start with equidistant steps in reduction of the threshold parameter. The size of these steps is then scaled with the resulting relative variation of the RMS spot size from the previous step.

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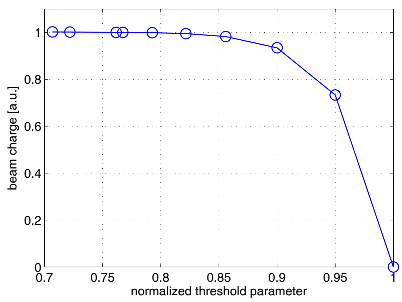


Figure 7: Example of the threshold iteration for a Gaussian spot. The sum of all pixels considered as beam is plotted against the threshold parameter. The normalized threshold parameter goes from the maximum value 1 to the minimum 0. At the maximum the whole image is considered to be *background* while at the minimum the whole image is *beam*.

If the threshold value is too high the beam is still partially cut. As a result the next step in the iteration increases the beam size. If the threshold value is low enough the beam is fully identified by the algorithm – a further reduction of the threshold includes only background to the beam which leads to saturation of the reconstructed spot size. In this regime the spot size change reduces which results in smaller steps of the threshold variation. The procedure stops if the relative changes of the beam size reach a predefined limit. An example is presented in Fig. 7. In this example we analyzed a Gaussian beam spot. The iteration starts at 1, reducing the value step by step. As the beam size (and thus the integrated pixel intensity, equivalent to the beam charge) saturates the step size is reducing. Because of noise in the image the step size is fluctuating at this level.

### *Halo Suppression*

Up to now our image analysis procedure is there to remove background allowing for well defined RMS spot size determination. It is *not* meant as a halo removal at this point. However an increase of the threshold value compared to the one determined in the last section has such an effect.

After determination of the *optimal* threshold (corresponding to 100% charge) value we are going back to a curve in Fig. 7. By interpolation the point corresponding to a certain percentage of the total charge is picked and then used as a threshold to determine a truncated beam size (e.g. 90% charge). As an example we used the same beam image as we used in the previous examples. A summary is given in Fig. 8.

## SUMMARY

We have presented a comparison between two methods of optics based emittance measurements. We come to the

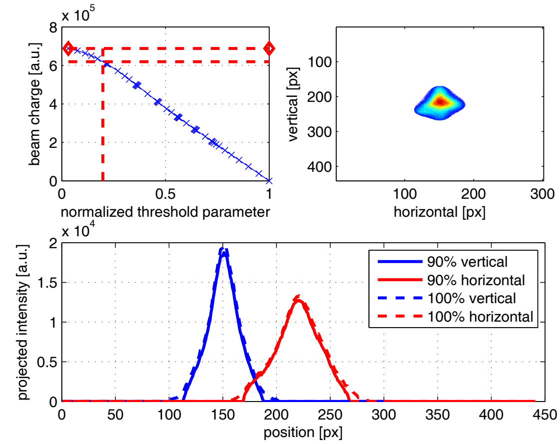


Figure 8: The upper left plot corresponds to Fig. 7. In addition the red lines indicate the total beam charge and the truncated one (in this case 90%). The upper right plot shows the truncated beam image containing now 90% of the total charge, and finally the lower plot is a comparison of the profiles of full and truncated charge.

conclusion that the multi-knob method is more powerful than a fixed-lattice approach. This is mainly because of the higher number of data points available compared to a typically available dedicated diagnostic FODO lattice.

Finally we presented some recent work on image post-processing to improve the spot-size determination for non-Gaussian shaped beams as an input to the the emittance calculation.

## ACKNOWLEDGEMENTS

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