SINGLE SHOT EMITTANCE MEASUREMENT FROM BEAM SIZE MEASUREMENT IN A DRIFT SECTION

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Abstract

Single shot emittance measurement is essential to assess the performance of new generation light sources such as linac based X-ray FELs or laser plasma wakefield accelerators. To this end, we have developed a single shot transverse emittance measurement using at least 4 screens inserted in the beam at the same time, measuring the beam size at different positions in a drift space in one shot. We present here test measurements performed at Diamond in the transfer line from the Booster to the Storage Ring, using thin OTR screens. Additionally, we compare these measurements with results from the more conventional quadrupole scan method. The validity and limits of the new method are also discussed.

INTRODUCTION

Next generation light sources such as linac based X-ray FELs or laser plasma wakefield accelerators will need to have a very small emittance with high shot-to-shot stability. Therefore, a single shot emittance measurement is needed to characterise the accelerators of these new light sources. There are several possible ways to measure the transverse emittance in a single shot. At Diamond, we have designed and commissioned a 2 m long section of the transfer line from the booster to the storage ring (BTS) for the development of new diagnostics for next generation light sources. We used this new diagnostics test stand to develop and demonstrate a novel method that uses four OTR screens to perform such a measurement. In this paper we present the method and the experimental results obtained on the Diamond BTS. We then discuss the strengths and the limitations of the measurement before giving some concluding remarks.

PRINCIPLE OF THE MEASUREMENT

In a drift space where dispersion does not contribute significantly to the beam size, this size (σ) evolves as [1]:

$$\sigma(s) = \sqrt{\epsilon(\beta_0 - 2\alpha_0 s^2 + \gamma_0 s^2)} \tag{1}$$

where s is the position in the drift space, β_0, α_0 and γ_0 are the Twiss parameters at $s = 0$ and ϵ is the beam emittance. When $s = 0$ is a symmetry point (waist), this can be rewritten as

$$\sigma(s) = \sqrt{\epsilon\beta_0 + \frac{\epsilon}{\beta_0}s^2} \tag{2}$$

By measuring σ with an OTR screen at 4 (or more) locations around a waist, it is thus possible to make a parabolic fit giving the Twiss parameters of the beam as well as ϵ and β_0.

In a drift space it is possible to rewrite expression 2:

$$\sigma(s)^2 = \sigma_0^2 + \frac{\epsilon^2}{\sigma_0^2}s^2 \tag{3}$$

Expression 3 will be used to fit the emittance, using the four OTR screens located in the diagnostics test stand in the BTS of Diamond.

EXPERIMENTAL SETUP

The diagnostics test stand in the BTS of Diamond is a 2 m long vacuum pipe that can be replaced by a vacuum chamber with beam diagnostics to be tested. For the purpose of these tests we have equipped it with four 6-way crosses in which an actuator inserts either OTR or YAG screens (see figure 1). The OTR screens are made of a 5 μm thick sheet of mylar, aluminised on both sides. Upstream from the screens are 3 pairs of quadrupoles and 6 correctors for the horizontal and vertical trajectories. The first screen is 2.3 m after the last corrector, and the other screens along the electron path are located 0.57 m, 1.07 m and 1.75 m after the first one. The screens are imaged by cameras with high resolution lenses with a 50 mm focal length, achieving a typical resolution of 50 μm on the screens. The cameras acquiring images of the screens are triggered so that single shot capture is ensured and verified by the image timestamps.

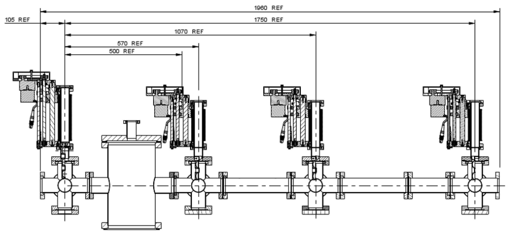

Figure 1: Experimental setup of the Diagnostics test stand of the BTS in Diamond.

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BEAM SCATTERING BY THE SCREENS

The main limiting factor for the proposed measurement is scattering from the screens. The scattering induced in the beam by a screen depends on its material and on its thickness [2]. This is discussed in detail in [3]. In order to evaluate the scattering effect we have measured the beam size on OTR 4, inserting all the possible arrangements of the other three screens. The results are summarised in figure 2. For the horizontal size, the broadening due to scattering is negligible. The beam size measured no other screen upstream is $\sigma_{x,4,0} = 836\ \mu$m. The statistical variation is approximatively 1% and no broadening is measurable with insertion of OTR screens. Insertion of YAG screens induces a broadening of approximatively 5%. The vertical beam size is smaller than the horizontal, $\sigma_{y,4,0} = 128\ \mu$m. The scattering is measurable and is typically 5% with OTR screens, and 100% with YAG screens.

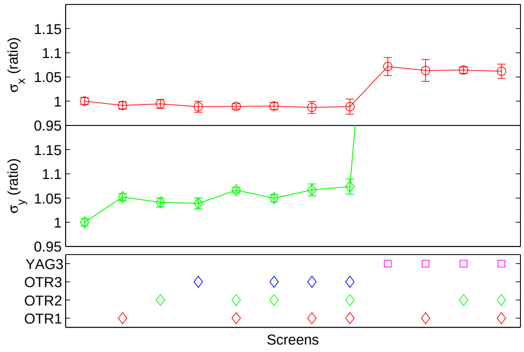

Figure 2: Beam size ratio measured on OTR 4, with all combination of screens inserted or not. The horizontal axis indicates which screens is inserted. For every combination, the mean value over 10 shots is plotted and the error bar represents the standard deviation. The reference beam size is for the case when no other screen is inserted.

SINGLE SHOT EMITTANCE MEASUREMENT

Single shot emittance measurements were carried out after setting the beam optics so that a beam waist could be seen between the second and third screens. From that reference optics, we scanned the pairs of quadrupoles and simultaneously recorded images of each shot in all four OTR screens. Analysis of the images was performed by fitting a two-dimensional Gaussian. Figure 3 shows a single shot of four OTR images where the ellipses are the results of the fit. The electron distribution is quasi Gaussian along the two axes. Analysis of the quadrupole scans shows the beam size envelope along the drift section. Figure 4 shows such an envelope, demonstrating the stability of the beam sizes.

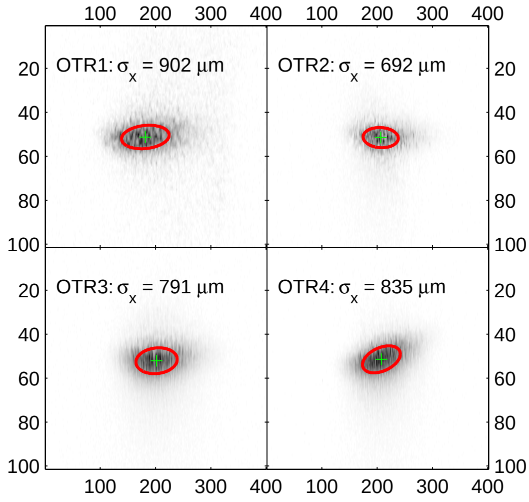

Figure 3: Horizontal beam size measured on images acquired in single shot on all four OTRs.

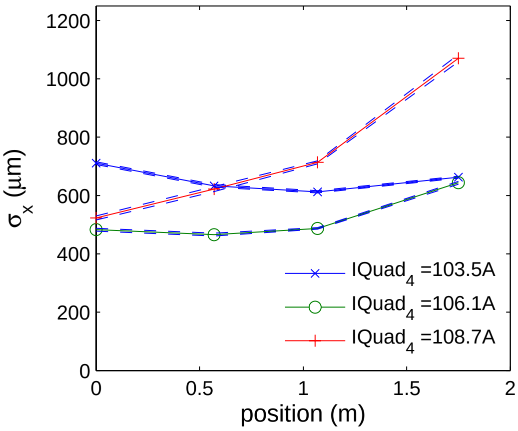

Figure 4: Horizontal beam size measured on images acquired simultaneously on all four OTRs and for 10 beam shots for each quadrupole settings. The dashed lines show the standard deviation of all shots as an envelope of the beam size.

Single Shot Emittance

Each measured beam size envelope at the four screen positions gives a measurement of the emittance, fitted with expression 3. Figure 5 illustrates such a fit procedure. The emittance found in the case is $\epsilon = 120$ nm rad. This values is 15% less than the nominal emittance of the 3 GeV electron beam in the BTS. We note that this is the first time that the emittance of the BTS is measured with such accuracy. Figure 6 presents the results of the single shot emittance using expression 3. The mean value over 250 shots across the scan of quadrupoles 1 and 2, is $\epsilon \approx 122$ nm rad, with a standard deviation, $\Delta\epsilon \approx 14$ nm rad. Another method to evaluate the emittance is by calculating the Twiss parameters (see figure 6). The top graph compares the emittances found from the two methods, and the other plots show the calculated Twiss parameters (α, β and γ) at the screen positions. The mean value of ϵ in this case is 129 ± 36 nm rad. The 36% variation of this method makes it less precise than the one based on expression 3, which shows 10% variation over the the full set of measurements.

This can be compared to typical emittance given by more conventional quadrupole scans, finding $\epsilon \approx 110$ nm rad. In the latter method knowledge of quadrupole strengths and betatron function is necessary to fit the emitance, whereas our present approach requires no knowledge on the machine.

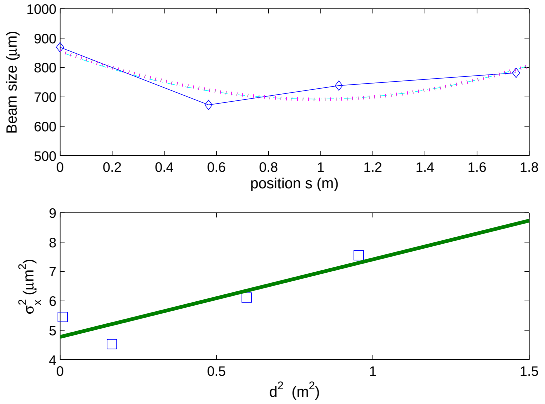

Figure 5: **Top plot**: envelope of the horizontal beam size for a single shot, and second order polynomial fit. **Bottom plot**: Beam size squared against the squared distance from the beam waist. The slope and the origin of the linear fit gives the emittance.

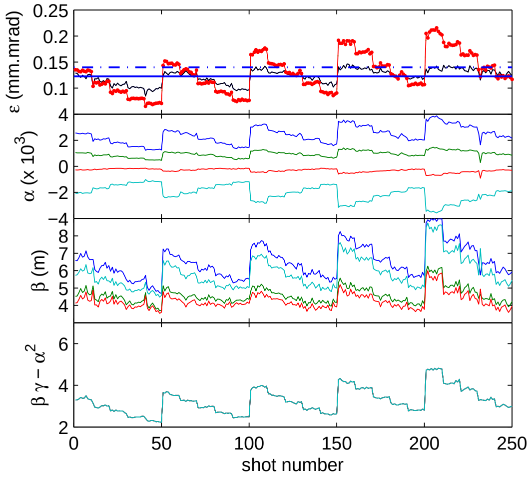

Figure 6: **top plot**: emittance calculated from expression 3, black line, and from the Twiss parameters fitted from beam sizes, dotted red line and their mean values, plain and dash-dotted lines respectively. **Second plot from top**: values of the calculated α at each screen. **Third and fourth plots**: same for Twiss parameters β and $\beta\gamma - \alpha^2$.

DISCUSSION AND CONCLUDING REMARKS

In this paper we have demonstrated single shot emittance measurements using four thin OTR screens. The results agree with more conventional methods, such as quadrupole scans. This method is shown to be robust, with 10% accuracy. It is relatively simple and does not assume any knowledge of the machine. This method provides an essential diagnostic for the development of future accelerators such as laser-driven plasma ones. The accuracy of the method can be improved. The resolution provided by the camera, typically 50 μm on the screen is sufficient for measuring several hundred μm beam size. However, the low intensity of the OTR photon flux induces statistical fluctuations in the images. Also, we have been fitting the beam size assuming two-dimensional Gaussian distribution, whereas measurement of FWHM emittance could provide more stable results.

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