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C. Rimbault J. Brossard P. Bambade M. del C. Alabau S. Kuroda A. Scarfe M. Woodley, Cécile Rimbault, J. Brossard, P. Bambade, M. del C. Alabau, S. Kuroda, A. Scarfe, M. Woodley

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4D EMITTANCE MEASUREMENTS USING MULTIPLE WIRE AND WAIST SCAN METHODS IN THE ATF EXTRACTION LINE

C. Rimbault, J. Brossard, P. Bambade, LAL, Univ Paris-Sud, IN2P3/CNRS, Orsay, France
M. del C. Alabau, IFIC(CSIC-UV), Valencia, Spain, S. Kuroda, KEK, Japan
A. Scarfe, Cockroft Institute, Univ. Manchester, UK, M. Woodley, SLAC, Stanford, USA

Abstract

Emittance measurements performed in the diagnostic section of the ATF extraction line since 1998 lead to vertical emittances three times larger than the expected ones, with a strong dependence on intensity. An experimental program is pursued to investigate potential sources of emittance growth and find possible remedies. This requires efficient and reliable emittance measurement techniques. In the past, several phase-space reconstruction methods developed at SLAC and KEK have been used to estimate the vertical emittance, based on multiple location beam size measurements and dedicated quadrupole scans. These methods have been shown to be very sensitive to measurement errors and other fluctuations in the beam conditions. In this context new emittance measurements have been performed revisiting these methods and newly developed ones with a systematic approach to compare and characterise their performance in the ATF extraction line.

INTRODUCTION

The Accelerator Test Facility (ATF) based at KEK consists of a S-band linac, a damping ring (DR) and an extraction line (EXT). The aim of ATF2 is to generate beams with stable very small spotsizes as required for future e^-e^+ linear colliders such as ILC or CLIC. The design, normalized horizontal emittance is 2.8×10^{-6} m·rad and the target value for the vertical emittance is 1% of this. This paper reports on emittance measurements in the ATF EXT performed since the end of 2007, in particular those from the 12 March 2008. The first idea was to check whether the large reconstruction errors affecting the vertical emittance in the presence of cross-plane coupling could play a role in explaining the increased values observed in the ATF EXT since 1998 [1], in addition to any genuine optical sources along the beam-line [2].

EMITTANCE MEASUREMENTS USING QUADRUPOLE AND SKEW QUADRUPOLE SCANS

The evolution of a σ beam matrix between two points, A and B, of an uncoupled transfer line is described by the following matrix equation:

$$\sigma^B = R\sigma^A R^T \ , \qquad (1)$$

where

$$R = \begin{pmatrix} R_{11} & R_{12} & 0 & 0 \\ R_{21} & R_{22} & 0 & 0 \\ 0 & 0 & R_{33} & R_{34} \\ 0 & 0 & R_{43} & R_{44} \end{pmatrix} ,$$

is the uncoupled linear transfer matrix between the two points.

In the ATF EXT, emittance can be determined by scanning beam sizes in a straight dispersion free section using wire scanners, as a function of the strength, k, of an upstream quadrupole (quad)[3]. The transfer matrix R between the quad and the wire scanner, can be expressed as the product the transfer matrix Q of the quad and the transfer matrix S from the quad to the measurement point, M. In the thin lens approximation, the transfer matrices for a quad, Q, and a skew quad, Q_K, are respectively:

$$Q = \begin{pmatrix} 1 & 0 & 0 & 0 \\ k & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -k & 1 \end{pmatrix} \quad Q_K = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{pmatrix} . \qquad (2)$$

The measured horizontal and vertical beam sizes, $\sqrt{\sigma^M_{11}}$ and $\sqrt{\sigma^M_{33}}$ at the wire scanner position can be then expressed as parabolic functions of the quad strength, each determined by 3 parameters:

$$\sigma^M_{ii} = k^2\sigma^Q_{ii}S^2_{ij} + 2S_{ij}k(S_{ii}\sigma^Q_{ii} + S_{ij}\sigma^Q_{ij}) + \\ S^2_{ii}\sigma^Q_{ii} + 2S_{ii}S_{ij}\sigma^Q_{ij} + S^2_{ij}\sigma^Q_{jj} = A(k-B)^2 + C \ ,$$

where $(i,j) \equiv (1,2)$ for horizontal beam size and (3,4) for vertical one. Fitting these parameters, A, B, C, enables the emittance, ϵ, and Twiss parameters, β and α, to be determined at the quad entrance:

$$\epsilon = \sqrt{\sigma^Q_{ii}\sigma^Q_{jj} - \sigma^{Q2}_{ij}} = \sqrt{\frac{AC}{S^4_{ij}}}$$

$$\beta = \frac{\sigma^Q_{ii}}{\epsilon} = \sqrt{\frac{A}{C}}$$

$$\alpha = -\frac{\sigma^Q_{ij}}{\epsilon} = \sqrt{\frac{A}{C}}(B + \frac{S_{ii}}{S_{ij}}) \ .$$

The same procedure can be used with the skew quads. The relation between measured beam sizes and sigma matrix elements at the skew position are then:

$$\sigma^M_{11} = k^2\sigma^{QK}_{33}S^2_{12} + k(S_{11}\sigma^{QK}_{13} + S_{12}\sigma^{QK}_{23})$$
$$+S^2_{11}\sigma^{QK}_{11} + 2S_{11}S_{12}\sigma^{QK}_{12} + S^2_{12}\sigma^{QK}_{22} = D_x(k-E_x)^2 + F_x$$
$$\sigma^M_{33} = k^2\sigma^{QK}_{11}S^2_{34} + k(S_{33}\sigma^{QK}_{13} + S_{34}\sigma^{QK}_{14})$$
$$+S^2_{33}\sigma^{QK}_{33} + 2S_{33}S_{34}\sigma^{QK}_{34} + S^2_{34}\sigma^{QK}_{44} = D_y(k-E_y)^2 + F_y\ .$$

Expressing the parabola fit parameters:

$$D_x = S^2_{12}\sigma^{QK}_{33} \qquad D_y = S^2_{34}\sigma^{QK}_{11}$$
$$-D_xE_x = S_{12}(S_{11}\sigma^{QK}_{13} + S_{12}\sigma^{QK}_{23})$$
$$-D_yE_y = S_{34}(S_{33}\sigma^{QK}_{13} + S_{34}\sigma^{QK}_{14})$$
$$D_xE^2_x + F_x = S^2_{11}\sigma^{QK}_{11} + 2S_{11}S_{12}\sigma^{QK}_{12} + S^2_{12}\sigma^{QK}_{22}$$
$$D_yE^2_y + F_y = S^2_{33}\sigma^{QK}_{33} + 2S_{33}S_{34}\sigma^{QK}_{34} + S^2_{34}\sigma^{QK}_{44}\ ,$$

one sees that a parabola not centered at zero ($E \neq 0$) is evidence for coupling.

The idea is to combine normal and skew quad scans in order to estimate the beam matrix elements [4]. In principle, one normal quad scan in both vertical and horizontal planes, and two scans of a skew quad at two measurement locations are enough to determine 9 of the 10 elements of the beam matrix. Experimentaly, skew scans in the horizontal plane are not usable for asymetrical beam emittances as produced in ATF, since the influence of the vertical beam size on the horizontal one is very small.

EMITTANCE RECONSTRUCTION USING BEAM SIZE MEASUREMENTS AT MULTIPLE WIRE POSITIONS

Projected emittance reconstruction based on multi-wire beam size measurements has been described in many papers [5, 6]. The principle of this method is to measure the horizontal and vertical betatron beam sizes at N different locations ($N \geq 3$), and, using the linear transfer optics matrices between all these positions, to reconstruct the sigma beam matrix at a given point, applying the matrix equation 1. Measuring the vertical beam size at 3 locations, A, B, and C, is sufficient to compute the projected vertical emittance $\epsilon_y = \sqrt{\sigma^A_{33}\sigma^A_{44} - (\sigma^A_{34})^2}$, where the sigma beam matrix elements have been determined by solving the following linear system:

$$\begin{pmatrix} \sigma^B_{33} \\ \sigma^C_{33} \\ \sigma^D_{33} \end{pmatrix} = \begin{pmatrix} (R^{AB}_{33})^2 & 2R^{AB}_{33}R^{AB}_{34} & (R^{AB}_{34})^2 \\ (R^{AC}_{33})^2 & 2R^{AC}_{33}R^{AC}_{34} & (R^{AC}_{34})^2 \\ (R^{AD}_{33})^2 & 2R^{AD}_{33}R^{AD}_{34} & (R^{AD}_{34})^2 \end{pmatrix} \begin{pmatrix} \sigma^A_{33} \\ \sigma^A_{43} \\ \sigma^A_{44} \end{pmatrix}$$

If $N > 3$, the solution can be found using a least squares method. Errors on the emittance and sigma beam parameter recontruction are estimated using a Monte-Carlo simulation and assuming gaussian errors on the initial beam size and dispersion.

An important difficulty in the multi-wire measurement method in the ATF extraction line is the sensitivity to the phase advance between wire scanners. In order to have a good vertical phase advance between wire scanners a matching procedure is under study for ATF2. In this procedure the Twiss parameter values at the entrance of the diagnostic section are required. These parameters can be deduced from quad scan or multi-wire measurements. Figure 1 shows the vertical phase advance, in the straight section of the extraction line, using Twiss parameters, and associated errors, deduced by both techniques for measurements presented in the next section. Each curve is obtained for one given (α_y, β_y) Twiss doublet. The solid and dashed red curve shows, respectively, the mean and the mean±rms values for 100 trials. A main conclusion is that the quad scan method constrains more the vertical phase advance than the multi-wire one.

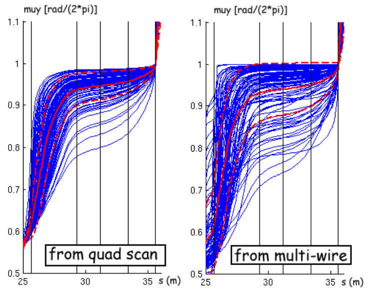

Figure 1: Vertical phase advance reconstruction in the diagnostic section of the ATF EXT from QF6X scan and multi-wire Twiss parameter estimations given in Table 1.

EMITTANCE MEASUREMENTS FROM 12 MARCH 2008 AND COUPLING STUDIES

Emittance measurements were performed in the ATF EXT using, successively, the two methods described above. The vertical emittance measured in the DR was about 34 pm·rad. Two quad scans were performed with QF5X (displayed in figure 2) and QF6X at wire scanner MW3X, respectively for vertical and horizontal plane, in addition to a

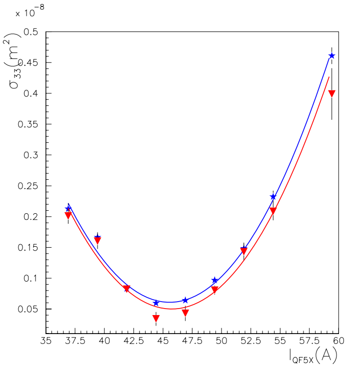

Figure 2: σ_{33} as a function of QF5X intensity. Blue stars correspond to the measured beam size, red triangle are corrected from the dispersion.

skew quad scan QK3X which is used for coupling estimation. Beam sizes were then measured at four wire scanner stations. The vertical emittance reconstructed by these two methods were respectively found to be, 114 ± 13 pm·rad and 82±25 pm·rad, which is three times the emittance measured in the DR. Table 1. shows the Twiss parameters reconstructed at QF5X, QF6X and MW0X. The parabola reconstructed from QK3X showed an explicit coupling since it was not centered at zero. A possible source of coupling is the QM7 quad, shared by the DR and the EXT [2], since the beam orbit is shifted horizontally. Using simulation based on the current machine status, reconstructed Twiss parameters were back-propagated to the entrance of the EXT and used as inputs for a MAD8 simulation. The goal was to try to reproduce both QK3X and QF5X measurements by adding a virtual skew quad as a coupling source It was achieved for a skew quad set at QM7 with a strength of $0.01547m^{-1}$, however requiring to also set the vertical emittance value at the EXT entrance to 51 pm.rad. This coupling corresponds to a vertical offset in QM7 of 0.33mm [7]. As it is shown on Figure 3, experimental data could so be fitted combining two virtual skew quads, set respectively at QM7 and at the downstream bending magnet BS1X, with half of the previous strength for each. The conclusion is that QM7 is not necessarily the only source of coupling in the EXT. Once the coupling is well reproduced, it should be possible to predict with simulation a well adapted coupling correction with the four skew quads of the ATF dispersion free section.

	QF5X	QF6X	MW0X
ϵ_x (nm.rad)	-	3.3 ± 0.4	3.3 ± 1.3
β_x (m)	-	24.4 ± 1.3	0.5 ± 0.2
α_x	-	-8.4 ± 0.7	0.7 ± 0.8
ϵ_y (pm.rad)	114 ± 13	-	82 ± 25
β_y (m)	9.1 ± 0.5	-	3.0 ± 2.2
α_y	10.5 ± 0.6	-	1.8 ± 2.0

Table 1: Emittances and Twiss parameters at QF5X, QF6X and MW0X.

CONCLUSIONS

Due to the very small vertical size of the ATF beam, vertical emittances are very sensitive to coupling sources. In order to measure and substract this coupling, a 4D sigma matrix measurement would be needed [5]. Additional tilted beam-size measurements at more than three wire scanner are then required. Another way to measure coupling is to performe skew quad scans with tilted wire in addition those presented in this article. In particular it would enable to reconstruct the entire beam matrix. More coupling studies are required to understand why the vertical emittance in EXT is still at least twice larger than the one measured in DR.

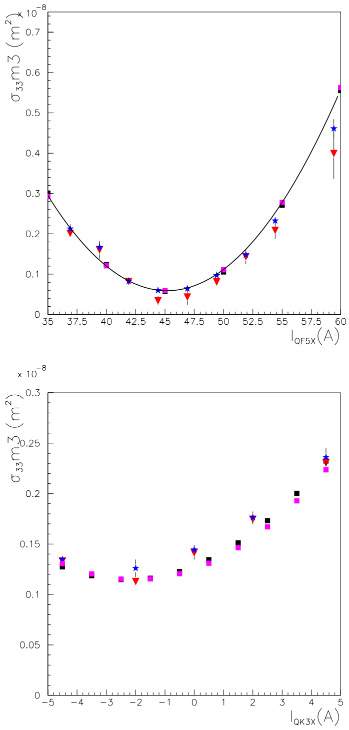

Figure 3: σ_{33} as function of QF5X (top) and QK3X (down) strength at MW3X. Blue stars correspond to the measured beam sizes, red triangles to the beam sizes corrected from the dispersion. The black and pink squares correspond to the simulated beam sizes using a coupling source, respectively at QM7 and both QM7 and BS1X.

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