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BENCHMARKING OF NEW APPROACH FOR ANALYZING TRANSVERSE BEAM EMITTANCE MEASUREMENTS

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Abstract

A recent analysis of emittance measurements highlighted the limited reliability of tools for precise method evaluation and error calculations. In this paper, a new analysis method is presented with its associated errors calculations. It is evaluated using realistic beam simulations and compared to the linear regression method commonly referenced in the literature. This new analysis method is shown to be easier to implement and provides results with a good confidence interval.

INTRODUCTION

This work is part of the studies made at the ALTO-LEB platform at IJCLab, Orsay, France [1] in the context of the reliability of the installation. We got the opportunity to make emittance measurements during two experimental campaigns in Spring 2023 and Spring 2024. The particle beam leaving the source and its transport along the lines to the experimental devices have never been rigorously characterized [2].

During the experiments, many data were taken using the Allison scanner developed at IPHC laboratory [3, 4, 5] and others standard diagnostics tools available at ALTO-LEB. We adjust many beam line configurations and target parameters.

During the data analysis, in order to determine the transverse beam emittance, we identified many difficulties to be confident in the obtained results. Using a common method to determine the emittance, we observed that the literature was poor concerning some precision of the analysis in terms of errors bars, Twiss parameters values and how to apply the method. We decided to push forward the development of a new method which will give us the complete knowledge of a beam: emittance, Twiss parameters and errors bars. A detailed paper have been recently submitted to review concerning the new approach [6]. The objective of the present proceeding is to give a short view of this new analysis method and present basic results obtained experimentally at ALTO-LEB.

FEW KEY POINTS ON EMITTANCE

The transverse emittance definition is given by [7] :

$$\varepsilon_{x,rms} = \sqrt{\sigma_x^2 \sigma_{x'}^2 - \sigma_{xx'}^2} \quad (1)$$

With :

$$\sigma_x^2 = \langle x^2 \rangle - \langle x \rangle^2 = \varepsilon_{x,rms} \beta \quad (2)$$

$$\sigma_{x'}^2 = \langle x'^2 \rangle - \langle x' \rangle^2 = \varepsilon_{x,rms} \gamma \quad (3)$$

$$\sigma_{xx'} = \sum_{i=1}^N \left(\frac{1}{N} (x_i - \langle x \rangle)(x'_i - \langle x' \rangle) \right) = -\varepsilon_{x,rms} \alpha \quad (4)$$

Where N is the total number of particles and α, β, γ are the Twiss parameters which verify $\beta\gamma - \alpha^2 = 1$. Equations are also valid in other planes.

In order to fully characterise a beam, the emittance but also the Twiss parameters are required. The Twiss parameters values are often missing in literature. In addition, the literature is too poor in the explanation of the errors associated to the measurement of beam emittance which is clearly necessary [8, 9].

In [6], we give the details of the expressions of errors which intervent in measurements made using Allison scanner system [10]. Basically, in a Allison scanner, errors are coming from the position δ_x of the mechanical system measurement (the motor and slit aperture), the divergence $\delta_{x'}$ link to the voltage applied between the plates and the integrated current at each step δ_I (which integrate all electronic errors). Reference [6] give all the detailed expressions of the propagation of these errors on emittance and Twiss parameters but they can easily adapt for other types of emittance measurements like Pepperpot systems as example.

In our context using an Allison scanner, the control panel is presented Figure 1.

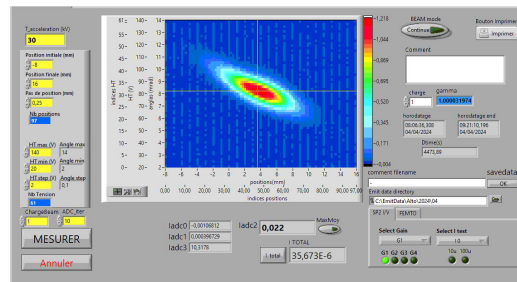


Figure 1: LabVIEW panel with an example of an emittance measurement with some of its parameters. The yellow area on the left indicates the parameters accessible to the user (beam energy, limits, position steps, voltage steps).

In the following, we will study from well-known beam emittance distributions, the results that we can be obtained using two analysis methods: the commonly used linear regression method and our new approach. Finally, we give an example of what we can obtain at ALTO-LEB.

INPUT DATA

For doing the comparison between the two analysis method, we need to start from a well-known beam particle distribution. For this purpose, we have used the TraceWin simulation tool developed at CEA-Saclay [11]. This tool is

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currently intensively used as example at SPIRAL2, DESIR or S3 at GANIL-Caen, ESS Lund, LINAC4 at CERN, MYRRHA at SCK CEN Mol. This tool is strongly versatile for our purpose.

We construct various particle distributions with different sizes, slopes, shapes and emittance generated following the Uniform 4D hyper-ellipsoid (Fig. 2). Geometrical emittance with 10^9 particles varied from $1\pi \cdot \text{mm} \cdot \text{mrad}$ up to $80\pi \cdot \text{mm} \cdot \text{mrad}$.

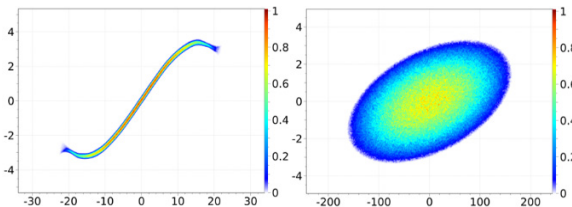


Figure 2: Two examples of beam particles distribution used for the benchmark between the two analysis methods. Left picture : $\epsilon_{rms} = 4.2 \pi \cdot \text{mm} \cdot \text{mrad}$, $\alpha = -4.9 \pi^{-1}$, $\beta = 21.3 \text{ mm}/\pi \cdot \text{mrad}$. Right picture : $\epsilon_{rms} = 80 \pi \cdot \text{mm} \cdot \text{mrad}$, $\alpha = -0.5 \pi^{-1}$, $\beta = 55 \text{ mm}/\pi \cdot \text{mrad}$.

Background noise with variable level can be added to the known particle distribution in order to simulate a real signal.

LINEAR REGRESSION

Beam emittances can commonly be determined using a linear regression [5, 8, 9]. The signal analysis is based on gradual subtraction channel to channel of a fraction of the maximum measured or generated signal using:

$$I_i = I_{mes} - \frac{n}{100} I_{max} \quad (5)$$

Figure 3 shows the typical emittance variation as a function of the threshold level apply to the signal. We include in the analysis error bars and limit conditions.

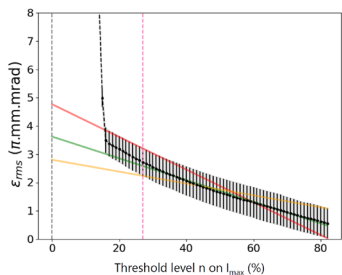


Figure 3: Emittance variation as a function of the level n applied to the full signal. In black the real values, in green the adjusted 1st order polynome, in red and orange, the limit of 1st order polynome by taking into account errors.

We clearly observed that the projected emittance at 0 threshold level is very sensitive to error amplitudes but also to the limit conditions. A careful attention must be paid to the profile of the emittance where more than one linear regression is visible. This comes from various aspects like the phase space particle distribution, non-linearities. Consequently, this method presents too large uncertainties on the emittance and Twiss parameters in order to be considered sufficiently reliable.

NEW METHOD

Considering this technique insufficiently robust, we decided to push the analyses further.

The new method is based on gradual subtractions channel to channel of a percentage of the total signal:

$$I_i = I_{mes} - \frac{n}{100 \times N_{bin}} I_{tot} \quad (5)$$

Thanks to well-known particles phase space, we show that the correct rms emittance is the point where the slope change sharply and this point correspond to the location of the maximum of the second derivative (Fig. 4 and Fig. 5).

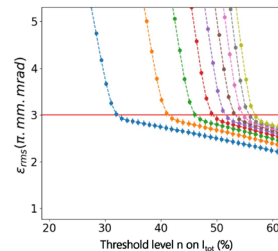


Figure 4: Emittance variation as a function of the threshold. In this case, emittance is well-known, curves correspond to different generated noise level.

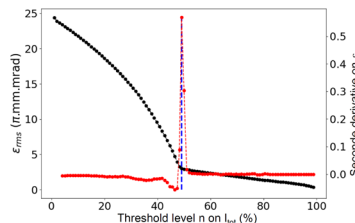


Figure 5: Emittance as a function of the threshold (black curve). Second derivative curve as a function of the threshold (red curve).

The determination of the maximum of the second derivative gives us directly the correct value of the emittance. Same method can be used for the Twiss parameters. This method include the errors and the implementation is easy.

We also studied in details how the signal to noise ratio, the step of the applied threshold and the steps of the measurement affects the results of emittance and Twiss parameters. We give here only the case of the impact of the measurements steps in position and divergence. This parameter is important because it is linked directly to the beam size and the corresponding emittance determination (Fig. 6).

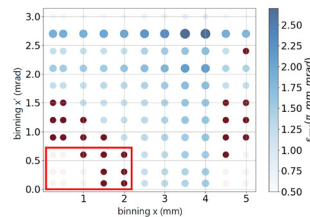


Figure 6: Emittance (theoretically to $1 \pi \cdot \text{mm} \cdot \text{mrad}$) as a function of the chosen step in position and divergence. Red rectangle shows the 10% confidence interval.

The smaller the emittance is, the finer the binning we need to choose. However, the longer the measurements will

be, with risks of instabilities. There is always a compromise between duration of a measurements and required precision.

ALTO-LEB RESULTS

Emittance measurements were carried out at the IJCLab ALTO-LEB research platform [1] to characterise the beam extracted from the target-ions source [2] (Fig. 7).

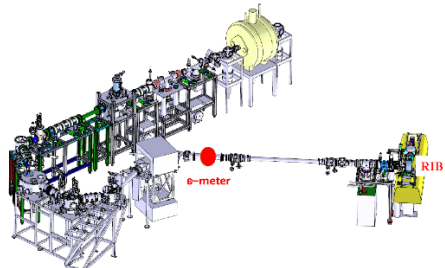


Figure 7: Selected view of the ALTO-LEB beam line from the RIB production up to an experimental set-up. The line is 20m long.

The Allison scanner developed at IPHC Strasbourg have been inserted at around 4m downstream the RIB production source because this location is the first one along the line with free space.

During the two experimental campaign, we studied many parameters: on the emittance-meter, beam line configuration, and RIB source parameters (temperature, extraction electrode location ...) [12]. For the analysis of the different measurements, the new analysis method was applied. We just give in this paper the results obtained for the nominal beam (Fig 8 and Fig. 9) which is the true transported beam with a maximal transmission from the sources up to as close as possible the experimental set-up for which the commissioning is on-going.

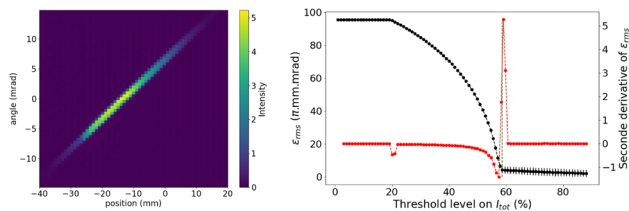


Figure 8: Horizontal phase space and emittance analysis for the nominal beam at ALTO-LEB at the location of the IPHC emittance-meter.

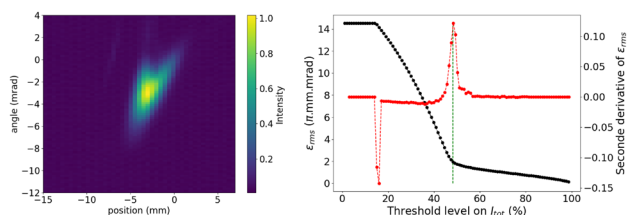


Figure 9: Vertical phase space and emittance analysis for the nominal beam at ALTO-LEB at the location of the IPHC emittance-meter.

The emittance and the Twiss parameters in the horizontal plane and in the vertical plane are :

- $\epsilon_{rms,x} = 4.2 \pm 2.2 \pi . mm.mrad$,
 $\alpha_x = -9.7 \pm 5.2 \pi^{-1}$, $\beta_x = 19.2 \pm 10.3 mm/(\pi.mrad)$
- $\epsilon_{rms,y} = 2.0 \pm 0.3 \pi . mm.mrad$,
 $\alpha_y = -0.7 \pm 0.1 \pi^{-1}$, $\beta_y = 1.0 \pm 0.1 mm/(\pi.mrad)$.

We can observe that emittance is larger in the horizontal plane than in the vertical plane and errors bars are also larger. The nominal beam in the horizontal plane is strongly defocus and less defocus in the vertical plane at the Allison scanner location. Other measurements with different focusing condition using the upstream quadrupoles show a better agreement between the horizontal and vertical plane. As already mentioned, a large beam in terms of transverses sizes with small emittance will quickly give a larger emittance than in reality and with larger errors. The discrepancy for the emittance between horizontal and vertical plane may come from the non identical condition in the RIB sources in both planes. A dedicated R&D program is already started to increase our understanding of the ionisation in the source.

CONCLUSION

In this paper, we present a summary of the emittance studies done at the ALTO-LEB installation at IJCLab Orsay. These studies have been done in the context of the reliability development. Beam emittance and Twiss parameters were characterised using a Allison scanner developed at IPHC Strasbourg. During the analysis we show that common method is not reliable. We developed a new technic in order to determine more rigorously emittance and Twiss parameters which included also errors propagation. This method can be applied for other type of diagnostic tools dedicated to emittance like pepperpot emittance meter.

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