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Emittance measurements in low energy ion storage rings

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ABSTRACT

The development of the next generation of ultra-low energy antiproton and ion facilities requires precise information about the beam emittance to guarantee optimum performance. In the Extra-Low ENergy Antiproton storage ring (ELENA) the transverse emittances will be measured by scraping. However, this diagnostic measurement faces several challenges: non-zero dispersion, non-Gaussian beam distributions due to effects of the electron cooler and various systematic errors such as closed orbit offsets and inaccurate rms momentum spread estimation. In addition, diffusion processes, such as intra-beam scattering might lead to emittance overestimates. Here, we present algorithms to efficiently address the emittance reconstruction in presence of the above effects, and present simulation results for the case of ELENA.

1. Introduction

Emittance measurement is essential in all particle accelerators and transfer lines to control and provide the required beam quality. There are many different ways to measure emittance ranging from simple beam optics techniques to new and advanced setups such as the supersonic gas jet based beam profile monitor [1]. In this paper we focus on expanding the capabilities of beam scraping through new data analysis and determine the limits of such a technique using particle tracking simulations.

Beam scraping enables direct access to information on the transverse phase space amplitude. It also presents a high dynamic range very suitable for getting information of low density long tails and halo measurements. Indeed, scraping by collimators has been used to measure beam halo diffusion and population in high energy colliders, e.g. in the Large Electron–Positron collider (LEP) [2] and Tevatron [3] in the past, and more recently in the Large Hadron Collider (LHC) [4].

Despite being destructive, the scraping method has also been used in many hadron machines for emittance measurement. Concretely, due to the simplicity of usage, it has been used with relatively low intensity antiproton beams in the Antiproton Decelerator (AD) [5,6], and a scraper device has been installed to measure emittances in the new ELENA storage ring [7].

As mentioned before, beam scraping is a destructive measurement technique. The beam is completely or partially removed by the scraper. Apart from measuring transverse phase space dimensions of the beam, scrapers can be used as collimators to reduce the size and intensity of the beam if necessary.

There are two types of scraper operation. In some cases the beam is progressively driven into a fixed limiting scraper aperture by means of steering magnets producing a local orbit bump. For instance, this is the functioning principle of the so-called BEAMSCOPE (BEtatron AMplitude Scraping by Closed-Orbit PErturbation) installed in the PS Booster at CERN [8]. However, the most common scraper operation mode is to move the scraper blades into the beam.

In order to directly access the information of the betatron phase space, scraper devices are preferably placed at energy dispersion-free positions in the optical lattice. For example, in the AD it is located in a position with zero dispersion. This simplifies emittance measurements since one does not have to deal with dispersive components. However, unlike the AD, there is no position with zero dispersion along the ELENA lattice. This will require a careful analysis of the finite dispersion on the signal and the design of efficient algorithms taking it into account.

An additional challenge is the emittance measurement for non-Gaussian beams. In several facilities, where electron cooling is a fundamental part and diffusion effects (rest gas and intrabeam scattering) are also important, the beam can adopt highly non-Gaussian beam distributions. For instance, beam profile measurements in the AD in the past [9] have shown non-Gaussian transverse beam distributions with a very dense core and long amplitude tails, generated during the beam cooling process (stochastic and electron cooling). In recent years such a core-tail beam structure in the AD has been confirmed using Gas Electron Multiplier (GEM) based beam profile monitors [10,11].

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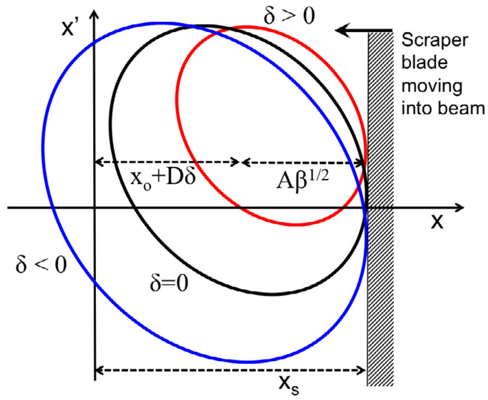

Fig. 1. Schematic of a scraper blade moving horizontally into a beam. The ellipses represent the acceptances for a beam with zero momentum offset (black), with positive momentum offset (red) and with negative momentum offset (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

After describing the principle of emittance measurements by scraping in Section 2, in Section 3 we briefly describe an algorithm for the particular case of Gaussian beams and propose an algorithm to calculate the emittance for arbitrary beam distributions. Simulations of emittance measurement by scraping in ELENA are shown in Section 4, followed by an analysis of various sources of errors. Finally, in Section 5 we draw some conclusions and plan for further studies.

2. Emittance measurements by scraping

In the algorithms developed below, we seek to determine the RMS value of the geometric transverse emittance, which may be defined statistically as:

$$\epsilon_{rms} = \langle J \rangle \equiv \frac{1}{2}\langle A^2 \rangle \tag{1}$$

where A is the amplitude of the particles in phase space, and J the action variable.

The principle of emittance measurements by scraping is based on a limiting aperture moving slowly into the beam to progressively remove the beam particles. Here, we consider the example of a metallic scraper blade moving slowly (compared to the revolution frequency) into the beam. Let us assume that the scraper aperture movement is slow enough such that the remaining beam intensity can be safely approximated by the fraction of the beam particles within the acceptance defined by the scraper position. Fig. 1 is a phase space plot to illustrate a horizontal scraper blade approaching the beam from the positive x-axis with a positive dispersion D.

Let us consider the normalised betatron phase space:

$$X_\beta = \frac{x_\beta}{\sqrt{\beta}}, \qquad X'_\beta = x'_\beta\sqrt{\beta} + \frac{x_\beta \alpha}{\sqrt{\beta}}, \tag{2}$$

where x_β and x'_β are the non-normalised particle betatron position and divergence angle in the beam, respectively, and β and α are the Twiss parameters in the corresponding transverse plane. The normalised amplitude in phase space is then given by $A = \sqrt{X_\beta^2 + X_\beta'^2}$, i.e.

$$A \equiv \sqrt{2J} = \sqrt{x_\beta^2\gamma + 2x_\beta x'_\beta\alpha + x_\beta'^2\beta}, \tag{3}$$

with $\gamma \equiv (1+\alpha^2)/\beta$ and J the action variable. The subindex "β" refers to the betatron component of phase space. If at the scraper position the first order dispersion is $D \neq 0$ and we assume a relative particle momentum offset $\delta \equiv \Delta p/p$, then the total position and angle can be written in terms of the betatron and dispersive contributions as $x = x_0 + x_\beta + D\delta$ and $x' = x'_0 + x'_\beta + D'\delta$, respectively, with $D' = \mathrm{d}D/\mathrm{d}s$. A displacement (x_0, x'_0) with respect to the reference closed orbit is also assumed.

A relative momentum offset $\delta > \delta_{max} := (x_s - x_0)/D$ corresponds to a closed orbit inside the scraper blade at position x_s; thus the transverse acceptance for parts of the initial beam with $\delta > \delta_{max}$ vanishes. For relative momentum offsets $\delta < \delta_{max}$, the transverse acceptance is determined by the distance $x_s - (x_0 + D\delta)$ between the momentum dependent closed orbit $(x_0 + D\delta)$ and the scraper position x_s. The acceptance for lower (higher) momentum offset δ corresponding to the blue (red) ellipse in Fig. 1 is larger (smaller) than for on-momentum particles (black ellipse).

The maximum oscillation amplitude defining the transverse acceptance is a function of the momentum offset given by:

$$A_{max} = \begin{cases} \dfrac{x_s - x_0 - D\delta}{\sqrt{\beta}} & \text{for } \delta < \delta_{\max}, \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

For the sake of clarity, the resulting acceptance in longitudinal and transverse phase space is depicted in Appendix A (Fig. A.18).

In general, before scraping a beam can be characterised by a distribution density:

$$\rho(\delta, A) = \rho_p(\delta)\rho_{\mathrm{T}}(\delta, A), \tag{5}$$

where the total density $\rho(\delta, A)$ can be represented as the product of two densities: the synchrotron amplitude distribution $\rho_p(\delta)$, expressed as a function of the relative momentum offset δ, and the transverse amplitude distribution $\rho_{\mathrm{T}}(\delta, A)$, which depends on A and intrinsically on δ through the dispersive component of the position.

The phase space density is normalised as follows:

$$\int_{-\infty}^{+\infty} \mathrm{d}\delta\rho_p(\delta) = 1, \tag{6}$$

$$\int_0^{+\infty} \mathrm{d}A 2\pi A\rho_{\mathrm{T}}(\delta, A) = 1. \tag{7}$$

Here, we will further assume the case of a coasting beam (the measurement of the emittance by scraping of a bunched beam may be more complicated) and no transverse plane (x–y) cross-coupling.

Taking into account the acceptance limits above, the remaining fraction of the beam in the machine with dispersion $D > 0$ is determined by the following integral:

$$F_+(x_s) = \frac{N_+(x_s)}{N_0} = \int_{-\infty}^{\delta_{max}} \mathrm{d}\delta\rho_p(\delta)\int_0^{A_{max}} \mathrm{d}A\ 2\pi\ A\ \rho_{\mathrm{T}}(\delta, A), \tag{8}$$

where N_0 is the number of particles in the machine before scraping and $N_+(x_s)$ is the number of particles left in the machine when the scraper is at x_s.

Similarly, if the scraper is coming from the negative x-axis, we obtain:

$$F_-(x_s) = \frac{N_-(x_s)}{N_0} = \int_{\delta_{max}}^{+\infty} \mathrm{d}\delta\rho_p(\delta)\int_0^{-A_{max}} \mathrm{d}A 2\pi A\rho_{\mathrm{T}}(\delta, A). \tag{9}$$

The integrals above give the cumulative distribution functions (CDF) of the beam loss. With this information one can obtain the corresponding probability density functions (PDF) projected on x_s from the derivatives $f_\pm = \pm\mathrm{d}F_\pm(x_s)/\mathrm{d}x_s$,

$$f_+(x_s) = \int_{-\infty}^{\frac{x_s - x_0}{D}} \mathrm{d}\delta\rho_p(\delta) 2\pi\frac{x_s - D\delta - x_0}{\beta} \times \rho_{\mathrm{T}}\left(\delta, \frac{x_s - D\delta - x_0}{\sqrt{\beta}}\right), \tag{10}$$

$$f_-(x_s) = \int_{\frac{x_s - x_0}{D}}^{+\infty} \mathrm{d}\delta\rho_p(\delta) 2\pi\frac{D\delta + x_0 - x_s}{\beta} \times \rho_{\mathrm{T}}\left(\delta, \frac{D\delta + x_0 - x_s}{\sqrt{\beta}}\right). \tag{11}$$

An example of a CDF and its corresponding PDF for a Gaussian distribution is shown in Fig. 2. Details of the derivation of the function f_+ from F_+ are shown in Appendix A.