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CHARACTERIZATION OF HIGH DYNAMIC RANGE BEAM EMITTANCE

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Abstract

Measurements of hadron beam emittances with very high dynamic range, 10^6 and above, became available recently. This level of dynamic range is required for studying the origin and evolution of beam halo in high intensity hadron linacs. There are no known or commonly accepted metrics to describe such distributions. Using data from emittance measurements of a 2.5Mev H^- beam at the SNS Beam Test Facility (BTF), we demonstrate that most common emittance metrics such as the RMS emittance and the Halo parameter H are insensitive to low level features of the distribution. As a new metric, we propose an unambiguously computable invariant of linear symplectic transformations that captures features important for low loss beam transport.

INTRODUCTION

Beam halo is a loosely defined low-density distribution of particles with large oscillation amplitudes, which can reach the aperture of the beam line enclosure thus creating uncontrolled beam loss. Because of this association with beam loss, halo is of major concern for high power hadron linacs, which require very strict loss control to prevent radioactivation of the beam line. A commonly accepted upper level for uncontrolled beam loss of $\sim 1\, {}^{W}/_{m}$ can be used to estimate the upper fractional level of the particle density at the beam line aperture in an accelerator with average power of P: $f \sim 1/P$. The average power of modern hadron linacs has surpassed 1MW and future designs aim at 10MW and higher, which corresponds to $f = 10^{-6}$ and below. For a measurement system, an ability to resolve fractional details of the order of f is characterized by the Dynamic Range (DR): $DR \sim 1/f$. The DR close to 10^6 in 2.5MeV proton beam 2d emittance measurements has been achieved recently [1]. The emittance data are often presented in the form of 2d maps in phase space coordinates for visual inspection, but there is no commonly accepted metric to numerically characterize a distribution with very high dynamic range. In this paper we explore application of several metrics successfully used previously to describe the low and medium dynamic range distributions, namely the RMS emittance and the halo parameter, and propose a new metric, we dubbed RMt, which is better suited for capturing important features observed in high dynamic range measurement of real beam.

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MEASURING BEAM EMITTANCE WITH LARGE DYNAMIC RANGE

A slit-slit emittance scanner with high dynamic range is implemented at the SNS Beam Test Facility [2]. The layout of the scanner is shown in Fig. 1. A small area of the beam phase space is localized by passing beam through a pair of narrow slits. The charge in that area is measured using a Faraday Cup or a luminescent view screen. A dipole magnet between the slits and the detector clears particles scattered off the slit edges. The slits positions are scanned independently to cover the whole phase space area of the beam. The detector sensitivity is adjusted during the scan to ensure the optimal signal-to-noise ratio in the areas of high and low charge density.

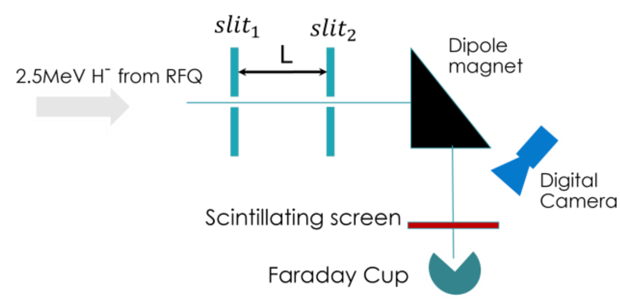

Figure 1: Schematics of the High Dynamic Range emittance scanner at the SNS beam Test Facility.

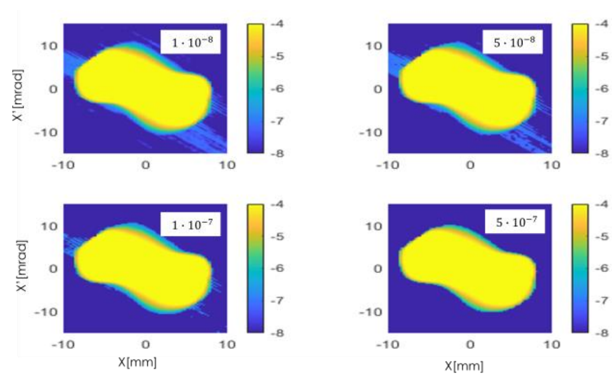

Figure 2: Emittance scan results for different values of noise cut-off threshold. The intensity scale is logarithmic and is adjusted to emphasize the low-level noise. The numbers in the text boxes show noise cut-off level relative to the peak of the distribution function.

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The noise is removed by zeroing intensity values below the cut-off threshold, which is found by visually inspecting the data, as illustrated in Fig. 2.

A typical phase space distribution with the dynamic range of 10^6 is shown in Fig. 3. This distribution is used for all calculations throughout the rest of the paper.

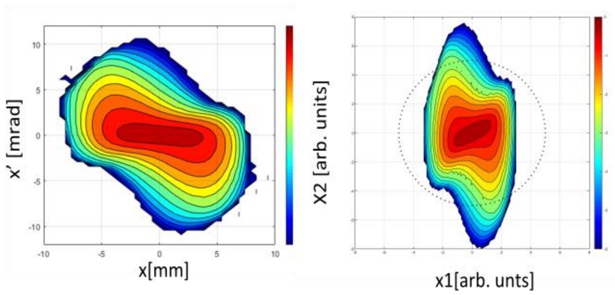

Figure 3: Horizontal emittance of a 2.5MeV H^- beam measured with 10^6 dynamic range. The intensity scale is logarithmic. The same distribution is shown in the natural (left) and normalized (right) coordinates. The dashed circle has $\mathbf{5 \cdot \sigma_{RMS}}$ radius in normalized coordinates.

NUMERICAL CHARACTERIZATION OF HDR EMITTANCE

The RMS Beam Emittance

The RMS emittance, defined as

$$\varepsilon_{RMS} = \sqrt{\langle q^2\rangle\langle p^2\rangle - \langle qp\rangle^2}\,,$$

where (q, p) is a pair of conjugate coordinates, i.e., x, x' or y, y', that are widely used for characterization of beam distributions in 2d phase space. It is natural to try it with a HDR emittance as well. The red curve in Fig.4 shows how the RMS emittance of the distribution from Fig.3 depends on the cut-off threshold. As the plot shows, a large portion of the distribution in the halo region can be removed without any appreciable change of the RMS emittance value. This result shows that the RMS emittance is not sensitive to low level details of the halo in real beam measurements.

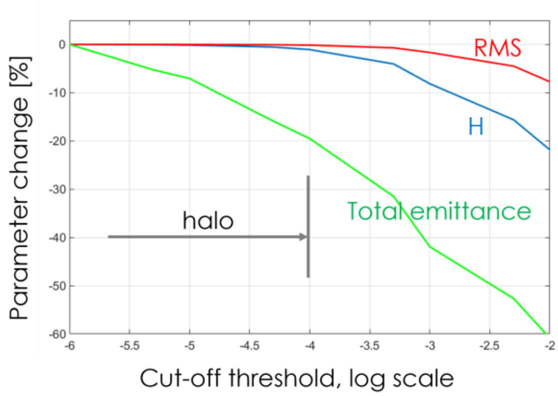

Figure 4: Dependence of the RMS emittance (red), Halo parameter (blue) and Total emittance (green) on the noise cut-off threshold, calculated for the phase-space distribution in Fig.3.

The Halo Parameter

The halo parameter H was proposed in [4] as an alternative to the RMS emittance, for its presumably higher sensitive to halo. It is defined as:

$$H = \frac{\sqrt{3\langle q^4\rangle\langle p^4\rangle + 9\langle q^2p^2\rangle^2 - 12\langle qp^3\rangle\langle q^3p\rangle}}{2\langle q^2\rangle\langle p^2\rangle - 2\langle qp\rangle^2} - 2$$

The halo parameter is invariant of symplectic linear transformations and is normalized to be zero for the Gaussian distribution. The blue curve in Fig.5 shows how the halo parameter calculated for of the distribution from Fig.3 depends on the cut-off threshold. As the plot shows, the H parameter is more sensitive than the RMS emittance, but still a large portion of the distribution in the halo region below 10^{-4} level can be removed without any appreciable change of the H value. This shows that the halo parameter is not sensitive enough to resolve details of the halo in modern hadron linacs.

The Halo ratio, Halo Mismatch and RMt Parameters

The total emittance ε_b is defined by the boundary enclosing all particles in the beam as illustrated in Fig.5 by the dashed line. It is reasonable to expect the total emittance to be closely related to the halo extent and beam loss. We can give a formal definition using equation of an ellipse with minimum area required to enclose all non-zero elements of a distribution in 2d phase space:

$$\gamma p^2 + 2\alpha qp + \beta q^2 = \varepsilon_b \;\;,$$

where α, β, γ are the Twiss parameters of the boundary ellipse. The green curve in Fig. 7 shows the dependence of the total emittance on the cut-off threshold for the distribution in Fig.3. Indeed, the total emittance is sensitive to the distribution relative density in the range of $10^{-6} - 10^{-4}$ and, thus can be used to characterize the halo.

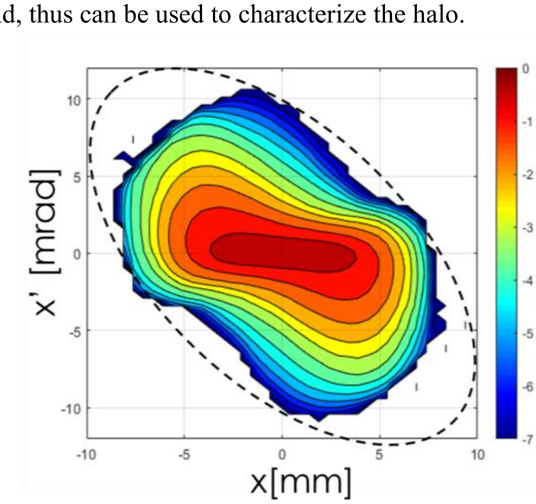

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Figure 5: Bounding ellipse for distribution with the dynamic range of 10^6 i.e., $t = 6$.

It is more convenient to use the dimensionless Halo Ratio parameter (R, t) defined as:

$$(R, t) = (\sqrt{\frac{\varepsilon_b}{\varepsilon_{RMS}}}, t)$$
$$t = -\log\left(\frac{f_{max}}{f_{min}}\right),$$

where f_{max} and f_{min} are the maximum and minimum of the distribution function.

The cut-off threshold is included explicitly in the definition to make the parameter unambiguously calculable.

The (R,t) parameter shows how much the beam size at the cut-off level is larger than the RMS size. For the distribution in Fig.3, (R,6) = 5.33, surprisingly close to the halo ratio parameter of the Gaussian distribution with the same RMS emittance, which is (R,6) =5.22. As it is customary to use the Gaussian distribution as a reference for comparison, we define the normalized parameter $(R_n, t) = (R, t)/(R_{Gauss}, t)$. For the distribution in Fig.3, $(R_n, t) = 1.02$. At the first glance, this number suggests that the beam with distribution we measured will have the maximum size in a periodic channel that is very close to the gaussian beam size. However, in an open-end system, such as a linac or a beam transport line, the beam size depends not only on the emittance but also on the matching conditions at the entrance. To capture this, we define the halo mismatch parameter (M, t) by calculating a well-known mismatch factor M [4] for the RMS and bounding ellipses:

$$M = \sqrt{\frac{R+\sqrt{R^2-4}}{2}},$$
$$R = \beta \cdot G + B \cdot \gamma - 2\alpha \cdot A,$$

and α, β, γ and A, B, G are the RMS and the bounding ellipse Twiss parameters correspondingly. For the phase-space distribution in Fig.3, The halo mismatch parameter (M,6) =1.58, which means the maximum beam size in a periodic channel will be ~58% larger if beam is matched for the RMS Twiss parameters at the entrance, compared to the size achievable if the bounding ellipse parameters are used for matching. By combining the (R,t) and (M,t) parameters in one RMt parameter we obtain a metric which describes features of a distribution in 2d phase-space important for the halo evolution in a focusing channel. For the distribution in Fig.3, RMt = (1.02,1.58,6), which indicates potentially significant beam size increase, e.g., halo, if the beam is matched for the RMS Twiss parameters. Almost no halo will be observed if the beam is matched for the bounding ellipse Twiss parameters. This is illustrated by plots of dependence of the average charge density in phase-space on the radius calculated for the RMS matching (blue curve) and the bounding ellipse matching (green curve) in Fig.8. The dashed curve is calculated for the Gaussian 2d distribution.

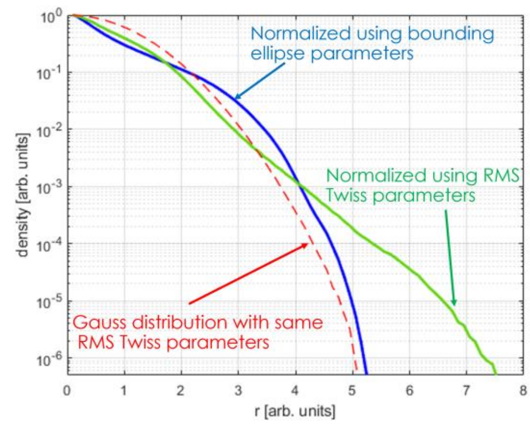

Figure 6: Phase space density plot normalized to the RMS (green) and the bounding ellipse (blue) Twiss parameters.

SUMMARY

We tried to use well-known metrics for characterizing a 2d phase-space distribution of 2.5MeV proton beam measured with dynamic range of 10^6, sufficient for detecting features relevant for beam loss during transport and acceleration. We found that the widely used RMS emittance and the halo parameter are not sensitive to the presence of particles below about ~10^{-4} relative to the peak charge density. We suggest a new metric, we call RMt, which reflects the maximum size of the low-density part of the distribution in a periodic focusing channel. This metric is unambiguously calculable, invariant in linear symplectic transformations and includes the charge density cut-off level explicitly. With more high dynamic range emittance measurements available for beam at different conditions at the SNS BTF, we will explore further the utility of the proposed metric in real life applications.

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REFERENCES

[1] A. Aleksandrov *et al.*, "First measurement of a 2.5 MeV RFQ output emittance with 1 part-per-million dynamic range", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 987, p. 01689002, 2021.doi:10.1016/j.nima.2020.164829

[2] Z. Zhang *et al.*, "Design and commissioning of the Beam Test Facility at the Spallation Neutron Source," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 949, p. 01689002, 202. doi:10.1016/j.nima.2019.162826.

[3] C. Allen *et al.*, "Beam halo definitions based upon moments of the particle distribution," *Phys. Rev. Accel. Beams,* vol. 5, p. 124202, 2002. doi: 10.1103/PhysRevSTAB.5.124202

[4] TRACE 3-D Documentation, LA-UP-97-886