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TECHNICAL REPORT

Minimum ellipse emittance analysis with SCUBEEx code

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ABSTRACT: Results of the first beam emittance measurements obtained at the SARAF 20 keV/u protons and deuterons low energy beam transport line were analyzed using the SCUBEEx code from SNS. In most of the measurements the code provides with robust emittance evaluation. However significant problems were encountered in the special cases of low currents beams. We found that use of the minimum ellipse rather than RMS ellipse as a SCUBEEx filter ellipse resulted in significant improvement in these cases.

KEYWORDS: Ion sources (positive ions, negative ions, electron cyclotron resonance (ECR), electron beam (EBIS)); Data reduction methods.

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2008 JINST 3 T02001

Contents

1. Introduction 1

2. An example of a typical case 2

3. An example of a difficult case 3

4. Alternative filter 5

5. Conclusion 6

1. Introduction

The linac in Soreq Applied Research Accelerator Facility (SARAF) will accelerate a few mA proton and deuteron beams up to 40 MeV [1],[2]. Commissioning of the first phase of the accelerator, including the ECR Ion Source (EIS), Low Energy Beam Transport (LEBT) system, Radio Frequency Quadrupole (RFQ) accelerator and buncher, Medium Energy Beam Transport system, Prototype Superconductive Module and a diagnostic plate, is currently in progress.

The beam emittance is defined as six dimensional distribution of particles coordinates and velocities, which usually is divided by three independent two-dimensional distributions. Beam emittance is an important beam quality parameter that allows one to describe beam transport, matching between the accelerator components and predict beam losses. High intensity deuteron beams are planned to be used at SARAF facility, while the facility has to satisfy the "hands on" requirement. Thus, demands on the beam emittance are stringent. Numerous emittance measurements with 20 keV protons and 40 keV molecular hydrogen and deuteron beams of various intensity were perform to demonstrate that the EIS and LEBT systems satisfy the specification arising from beam dynamics calculations (normalized emittance should be less than 0.2 π mm·mrad) [3].

Analysis of transversal emittance measurements is a complex procedure that can yield misleading results in the case of problematic, none elliptical distribution in phase space, data. The Self-Consistent Unbiased Elliptical Exclusion (SCUBEEx) code was developed at Oak-Ridge National Laboratory [4],[5]. The code allows one to obtain unbiased estimate for the root-mean-square (RMS) emittance. The SCUBEEx was discussed by the authors in detail in [4]-[7] and in references therein. In code "an ellipse, called the *filter ellipse*, whose shape and orientation closely approximates the contour lines in the central region of the beam is converged about the beam center while monitoring average background outside of the ellipse. As the ellipse is shrunk, the average background of data exterior to the ellipse is subtracted from interior data points and only these resulting interior points are examined. The resulting 'unbiased' emittance can be determined by large plateau regions observed in the RMS emittance versus filter ellipse size plots" [7]. The code allows for a choice of shape and orientation of the filter ellipse. However, typically ellipses with RMS Twiss parameters (*RMS ellipse*) are calculated for all data or the data above given thresholds and are used as a default choice for the filter. Thresholding of noise and tails may be useful for reliable estimation of the RMS Twiss

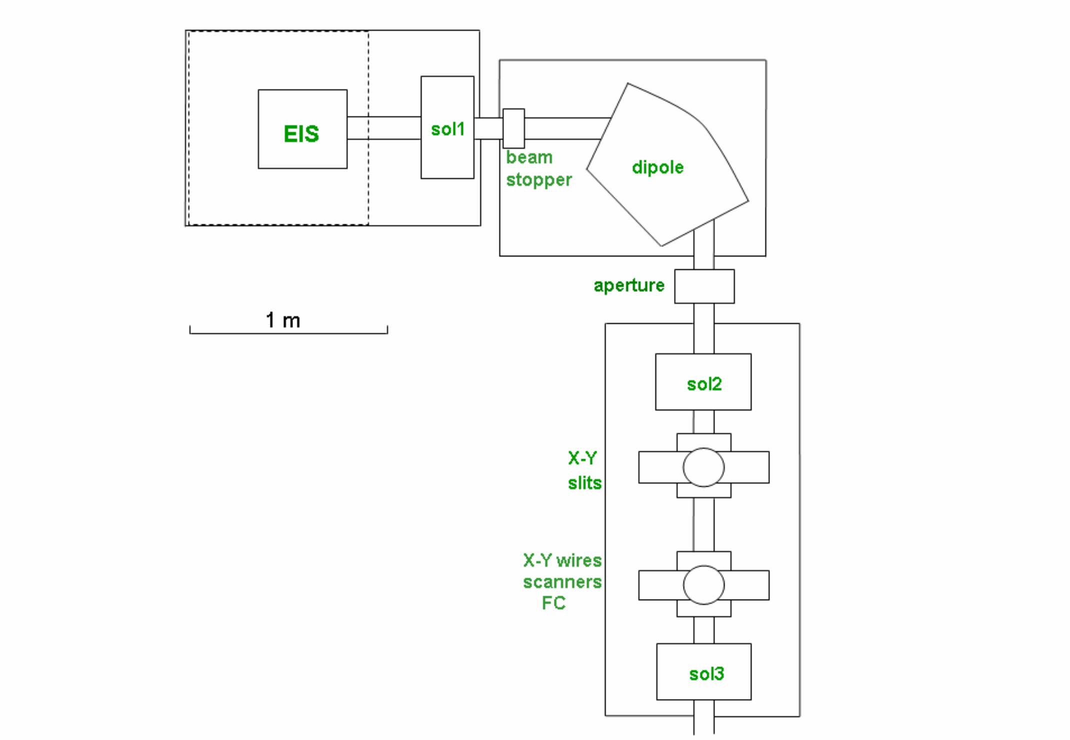

Figure 1. A schematic representation of SARAF LEBT beam line.

parameters. In the most cases the SCUBEEx analysis method is robust and is not very sensitive to the value of the threshold applied on the data for calculation of the RMS filter ellipse.

The purpose of this work is to test performance of the SCUBEEx analysis for various data obtained at the SARAF LEBT beam line. Details on the ion source, LEBT line and emittance measurements procedure and apparatus are given elsewhere [3]. Emittance was measured using vertical/horizontal slits and vertical/horizontal wire arrangement in the LEBT line (figure 1). The distance between the slits and wires was 59 cm. The slits are made from water cooled graphite. The slit gap is 0.1 mm. The wire is made of tungsten and its diameter is 0.1 mm. Typically 1 mm steps were used during slit and wire scans.

For most of the measurement the SCUBEEx analysis provided robust and unambiguous results. In the first section we examine a typical case where unambiguous results were obtained with analysis. A difficult case which leads to ambiguous results is presented in the second section. A special treatment of the latter case is discussed in the third section.

2. An example of a typical case

A typical measured phase distribution corresponding to 5 mA of proton beam is presented in figure 2. Typical features of this distribution are a strong elliptical core, weak S-shape tails and noise.

RMS ellipses calculated for this data at any possible choice of the threshold is readily used as a filter ellipse. Dependence of the shape of the RMS ellipse on the value of threshold is shown in the left plate of figure 3. It is evident that starting with 10 % threshold the shape of the RMS ellipse is constant. The results of the SCUBEEx analysis for several RMS filters are presented in the right plate of figure 3. There is no any ambiguity in the result of analysis. The normalized emittance of the source is within the specifications.

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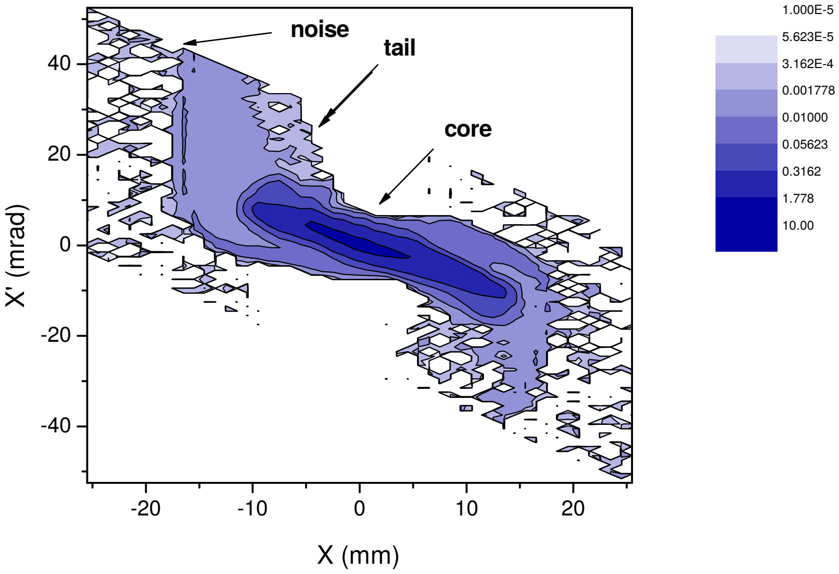

Figure 2. Phase distribution obtained for 5 mA 20 keV H^+ beams. Contour scale is logarithmic.

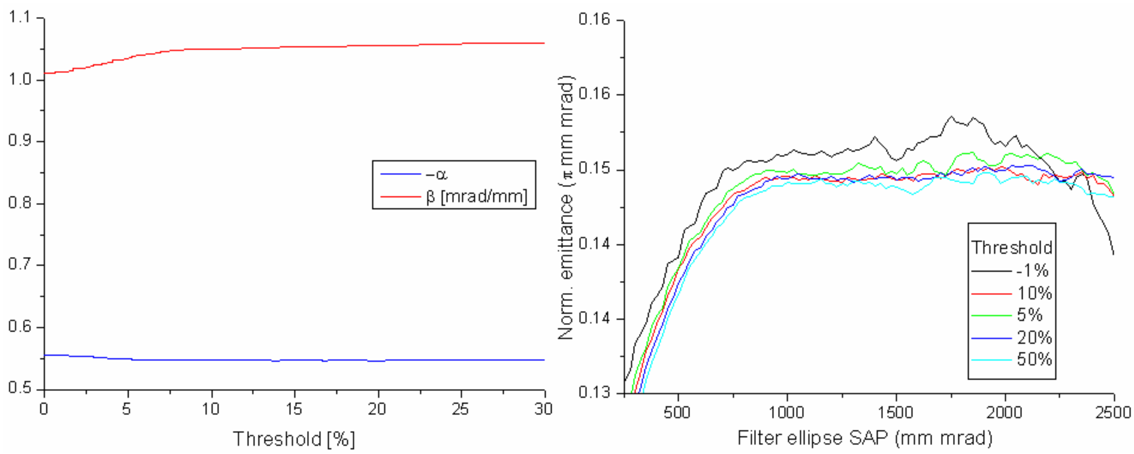

Figure 3. Left: Dependence of the RMS Twiss parameters as a function of threshold applied on the data. Right: Results of SCUBEEx calculations for various RMS filters. Normalized emittance as a function of filter area for different threshold values. The threshold values are indicated in the legend.

3. An example of a difficult case

Difficulties in analysis arouse for the specific cases of weak 40 μA beams. These low intensity beams are required in SARAF for irradiating targets that cannot hold an intense instantaneous beam current. The beams were obtained at rather unusual plasma conditions in the ECR source when nitrogen and hydrogen gases were mixed in approximately equal proportions as it was done in ref. [8]. An example of emittance measurement taken for 40 μA, 40 keV molecular hydrogen beam is shown in figure 4. The main problem in analysis is associated with the shape of distribution that does not exhibit a typical strong elliptical core. The factors that cause such distribution are not understood at the moment.

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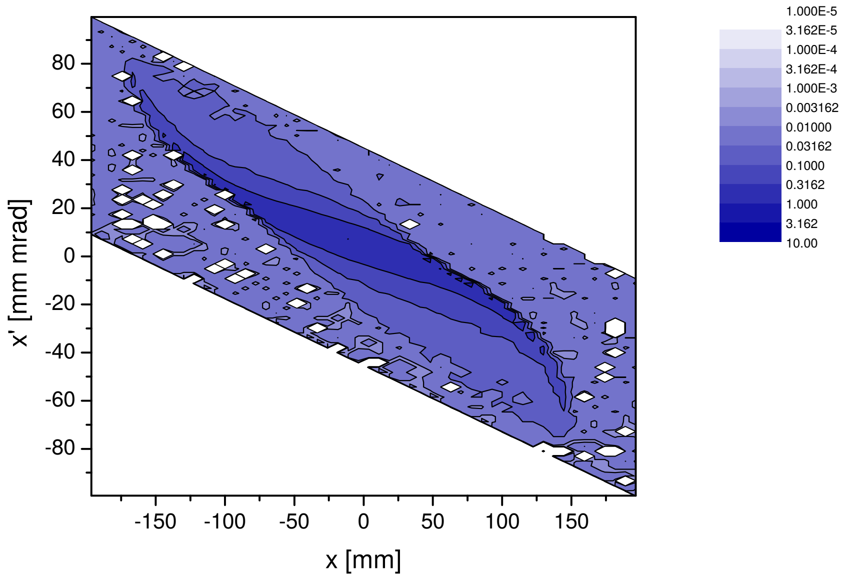

Figure 4. Phase distribution obtained for 40 μA 40 keV H_2^+ beams. Contour scale is logarithmic.

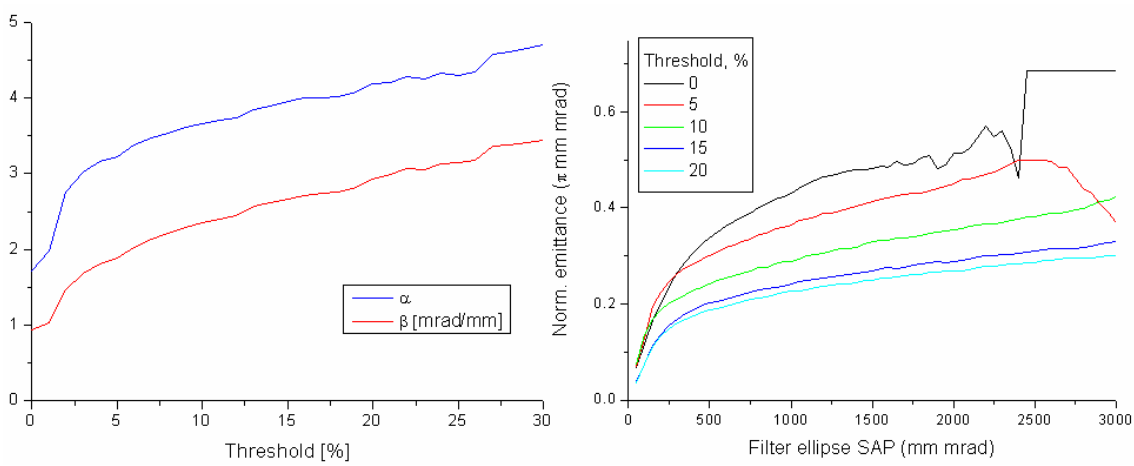

Figure 5. Left: Dependence of the RMS Twiss parameters as a function of threshold applied on the data. Right: Results of SCUBEEx calculations for various RMS filters. Normalized emittance as a function of filter area for different threshold values. The threshold values are indicated in the legend.

Dependence of the RMS Twiss parameters as a function of the threshold applied on the data (the threshold is defined as a fraction of the maximum current) is shown in figure 5-left. Unlike the case described in the previous chapter the RMS Twiss parameters do not stabilized even for the highest threshold values leading to large ambiguity in the emittance analysis. The results of the SCUBEEx analysis, based on the choice of the threshold value in calculating of the RMS filter, are shown in figure 5-right. One can observes in figure 5-right that: 1) the emittance does not reach plateau even for large filter areas; 2) there is a large discrepancy between SCUBEEx results for the different threshold values. Therefore the analysis does not allow for determination whether the emittance satisfies the specification value of 0.2 π mm·mrad.

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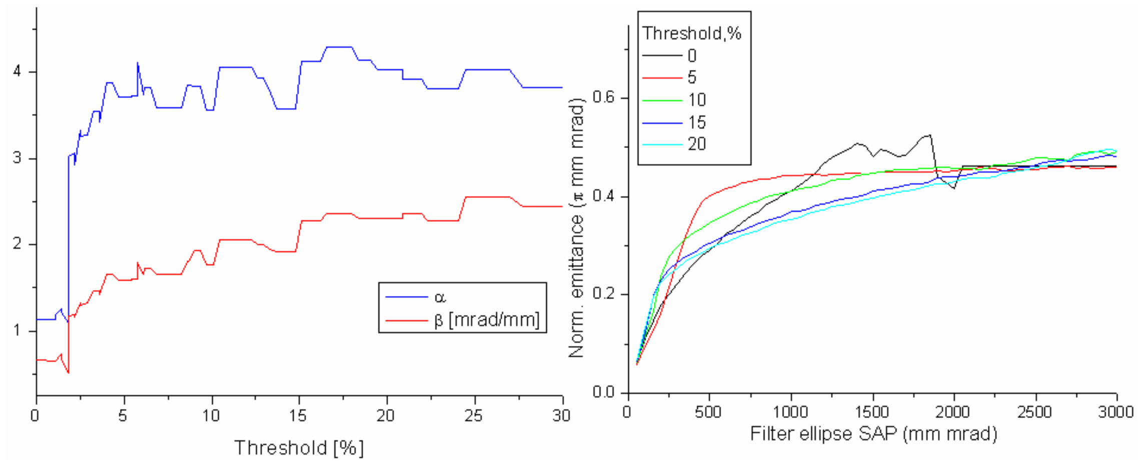

Figure 6. Left: Dependence of the ME Twiss parameters as a function of threshold applied on the data. Right: Results of SCUBEEx calculation for ME filters; normalized emittance as a function of filter area for different threshold values. The threshold values are indicated in the legend.

4. Alternative filter

The SCUBEEx analysis utilizing RMS ellipse was reported to be surprisingly robust in analysis of strongly curved distributions [5]. However, it is obvious that RMS ellipse is not a good filter choice for the distributions under consideration. The problem is most probably associated with the shape of the distribution that does not correspond to typical shapes of low energy beams, namely strong elliptical core and weak curved tails. In such situation one may attempt to find a filter ellipse which is more sensitive to area characteristics of the distribution rather than to the RMS parameters.

The concept of *minimum ellipse* (ME) criterion was introduced and developed in [9] where emittance was estimated by finding the minimum area ellipse which includes all data above a certain threshold. It was argued in [9] that this method gives better results than RMS emittance for the case of non elliptical distributions. We have determined minimum ellipses for the distribution presented in figure 4. However, rather than evaluating emittance using the ME method, our objective was to investigate performance of the SCUBEEx analysis for the ME filters.

The algorithm used for determination of minimum ellipse described in detailed in [9]. Minimization process starts with finding a first guess ellipse. The minimization of the area of the first guess ellipse then started by varying its Twiss parameters. The process is repeated for number of threshold values, so as a result the Twiss parameters of ME ellipse are determined as a function of the threshold applied on the data. The procedures of finding first guess ellipse, determination of the Twiss parameters for different threshold values are done by a specially written code.[1]

The Twiss parameters of minimum ellipse are shown in figure 6-left as a function of the threshold value. Examining the figure one can see that the shape of the ME ellipse stabilizes at relatively low thresholds of 5-10%. Thus, one expects that results of SCUBEEx will be much less sensitive to the choice of the threshold when the ME ellipse is used as a filter. Indeed, the results of the SCUBEEx analysis with ME filter (figure 6-right) show much smaller ambiguity when compared with results for RMS filter (figure 5-right).

[1] The code is available upon request from B. Bazak, b.bazak@gmail.com.

The result of the new analysis indicates that emittance of the molecular hydrogen beam does not satisfy the specifications. This fact is under investigation and will be addressed elsewhere.

5. Conclusion

The SCUBEEx analysis using RMS filter ellipses (default option in the code) yields satisfactory results in most data obtained at SARAF low energy beam line. However, we identified specific cases when use of RMS filter led to strong ambiguity in emittance determination. The problem is associated with non-typical shape of those specific distributions. We have shown that use of minimum ellipses as filters for SCUBEEx analysis yields much more satisfactory result for such a distribution. The results of the new analysis utilizing ME filter allowed us to verify that emittance of the low-intensity molecular hydrogen beam does not satisfy the SARAF requirement.

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