TRANSVERSE EMITTANCE MEASUREMENTS OF THE BEAMS PRODUCED BY THE ISOLDE TARGET ION SOURCES

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Abstract

The Isotope mass Separator On-Line DEvice (ISOLDE) is a Radioactive Ion Beam (RIB) facility based at CERN where rare isotopes are produced from 1.4 GeV-proton collisions with a target. The different types of targets and ion sources, operating conditions and ionization schemes used during the physics campaign results in extracted beams with various emittances. Characterizing the beam emittance allows deducing the transport efficiency to low-energy experimental stations (up to 60 keV) and the mass resolving power of the separators.

We report on emittance measurements for different beams of stable elements extracted from surface and plasma ion sources. The dependence of the emittance on the different conditions of operation of the ion sources is investigated and the results are compared to previous measurements.

INTRODUCTION

Motivation

Radionuclei are produced, ioniozed and accelerated in two separate frontends at ISOLDE before transport towards either the High-Resolution Separator (HRS) or the General Purpose Separator (GPS) [1]. The mass-resolving power of the separators is to first order, inversely proportional to the horizontal emittance of the beam. The characterization of the transverse beam properties is essential to determine the quality of beam transport to the low energy experimental stations, including the efficiency of trapping devices. The objective is to maximize the beam's brightness, which is proportional to the intensity and is inversely proportional to horizontal and vertical emittances.

Recent changes in the extraction electrodes and focusing elements of the frontends, coupled with the growing use of different types of target ion sources, motivated a review of the transverse properties of the beams produced at ISOLDE.

Definitions

We define the assumptions and sometimes necessary conventions used for describing the transverse properties of an ion beam.

The transverse projections are shown in the trace space $(u, u' = \frac{du}{dz})$ - non-normalized by the beam energy - with $u = x, y$ respectively for the horizontal and vertical plane. Using the Courant-Snyder invariant, the contours (u, u') of ion beams propagating through a focusing lattice describe ellipses [2]. The lengths of the beam ellipses' semi-axes are hereafter derived using the root-mean-square (1-rms) norm. When assuming a bi-Gaussian density distribution, a beam ellipse of size 1-rms encloses 39% of the particles. The value of the emittance $\varepsilon_{x,y}$ is calculated as the product of the semi-axes of the beam ellipses, and displayed in units of π.mm.mrad.

The effect of space charge on the particle motion is neglected after investigating the perveance of the beams used. The generalized perveance parameter K appearing in the Courant-Snyder equation is:

$$K = \frac{q \cdot I}{2\pi \epsilon_0 m (\gamma \beta c)^3} \quad (1)$$

The relativistic term $(\gamma \beta c)$ is evaluated for beam energies between 30 to 60 keV/u and a mass 200 amu. With peak current values I limited to 1 μA during the measurements and considering singly-charged ions, the generalized perveance remains below 10^{-9}.

EXPERIMENTAL SETUP

A schematic of the frontends installed at ISOLDE is shown in Fig. 1, it displays the target ion source vessel, the extraction electrodes, and the first electrostatic elements used to steer and focus the beam post-acceleration.

Target Ions Sources

The transverse properties of extracted beams were measured for three types of ion sources differentiated by the scheme of ionization and selection: surface ionizing, plasma ionizing and Laser Ion Source and Trap (LIST). The first type of ion source listed is efficient for alkalis, rare earth elements and molecules with low ionization potentials. The second type of ion source listed involves the creation of a plasma in a chamber between the line and extraction electrode. The region is subject to a magnetic field and an anode voltage to ionize a mixture of noble gases and generate secondary electrons adding the scheme of electron impact ionization at energies of a few hundred eV. Finally, the LIST-type of targets is a recent upgrade of the Resonance Ionization Laser Ion Source (RILIS), with the addition of an RFQ serving as an ion guide and repellers to suppress isobaric contaminants stemming from surface ionization. After extraction from the ion source, the beam is centred and sent parallel to the first quadrupole triplet via a pair of electrostatic steerers. A selective overview of the ISOLDE literature on ion sources can be found in [3] [4].

Quadrupole Scan Method

The principle behind the quadrupole scan method is to measure multiple transverse profiles for different known transformations of the beam ellipse and apply a fitting to deduce the emittance and Twiss parameters. The first

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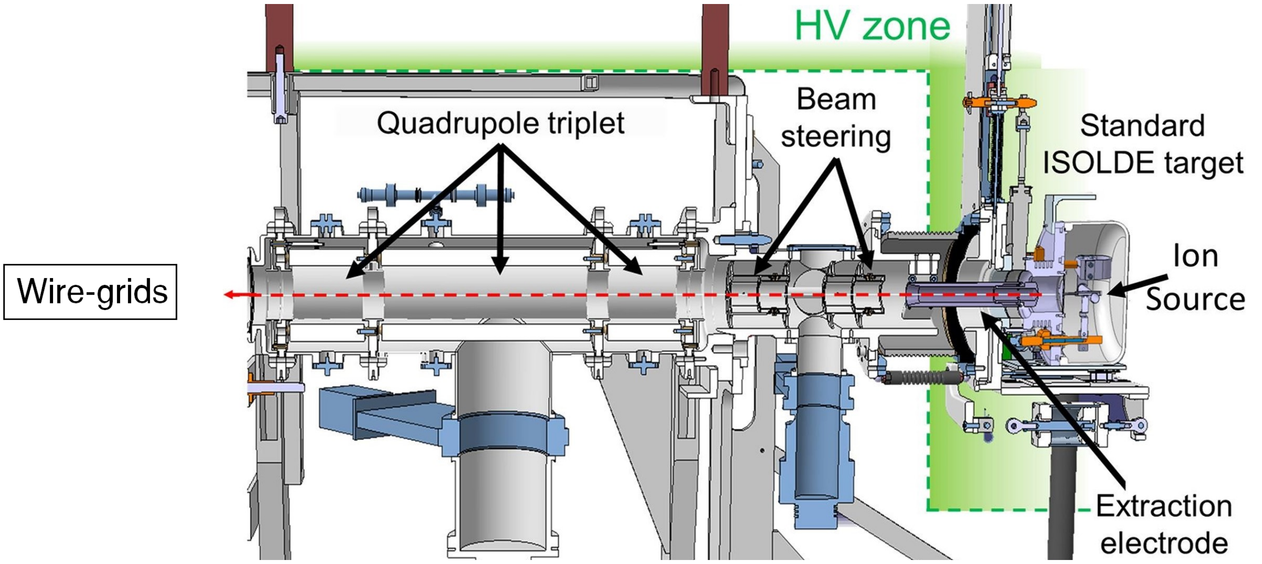

Figure 1: Schematic of the ISOLDE frontend of the GPS (FE10 and FE11). Courtesy of Stefano Marzari, CERN.

quadrupole of the triplet is used the shape the beam, and the second and longest (L_{QP} = 48 cm) quadrupole provides a varying electrostatic focusing. The third quadrupole is kept off, drifting the beam to a wire grid to measure the transverse profiles. The wire spacing of the beam profile monitor is 0.5 mm, and the electrical sensitivity ranges from 20 pA to 2 mA.

Varying the quadrupole's focusing implies a change in the transverse rms noted $\langle u^2 \rangle = \sum f(u-\bar{u})^2$, which is also equal to the product of the β-function and the emittance. The entire σ-matrix of the beam is,

$$\sigma = \varepsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} = \begin{pmatrix} \langle u^2\rangle & \langle uu'\rangle \\ \langle uu'\rangle & \langle u'^2\rangle \end{pmatrix} \tag{2}$$

The transformation of the σ-matrix through the focusing and drift region is, $\sigma\left(z_j\right) = \mathcal{R}\sigma\left(z_i\right)\mathcal{R}^T$, with the transfer matrix $\mathcal{R}$,

$$\mathcal{R} = \begin{pmatrix} 1 & L_{QP} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \cos\phi & \frac{1}{\sqrt{k}}\sin\phi \\ -\sqrt{k}\sin\phi & \cos\phi \end{pmatrix} \tag{3}$$

The factor $\phi = \sqrt{|k|}L_{QP}$ requires estimating the focusing strength k of the quadrupole for the different pole voltages used, which is done using COSY INFINITY [5]. The theoretical evolution of $\sigma_{11}(k)$ at the location of the wire grids resembles a parabolic curve and is fitted to the data sets for deducing the Twiss parameters and emittance. In practice, the quadrupole's focusing is varied twenty times per series of measurements, such that the waist of the beam is captured, and a sufficient rotation angle $\tan\theta = \frac{\mathcal{R}_{12}}{\mathcal{R}_{11}}$ is covered. A cumulative integration time of one minute per individual beam profile allows satisfactory uncertainties on the variance (or σ_{11}), limited by the wire spacing geometry or beam instabilities.

DATA TREATMENT

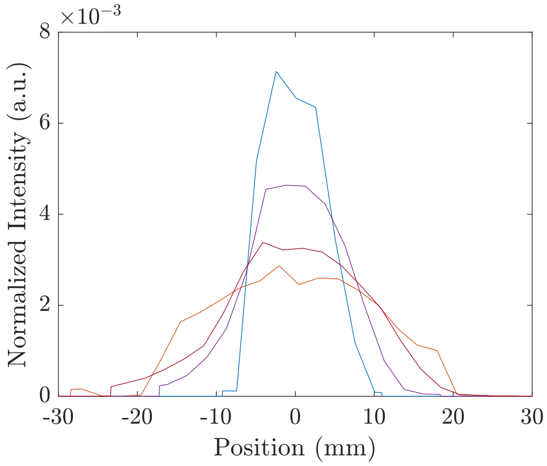

Figure 2: Typical vertical beam profile acquired for four different focusing strengths during the quadrupole scan method.

The transverse beam profiles are first treated to remove the noise bias by looking at the average value of the current read without beam impinging. Secondly, a threshold is chosen for each profile, equaling a certain number of times the initially measured rms, so that the values beyond the interval are set to zero. The value of the threshold, noted χ, is set by investigating the evolution of the second derivative of the emittance and the Twiss parameters as a function of the exclusion interval size. A typical example of beam profile acquisitions and the resulting second derivatives leading to the deduction of the threshold is shown in Figs 2 and 3. In this case, the threshold is chosen to be about $\chi = 4$, four times the initial rms value, with the resulting fitting on σ_{11} shown in Fig 4.

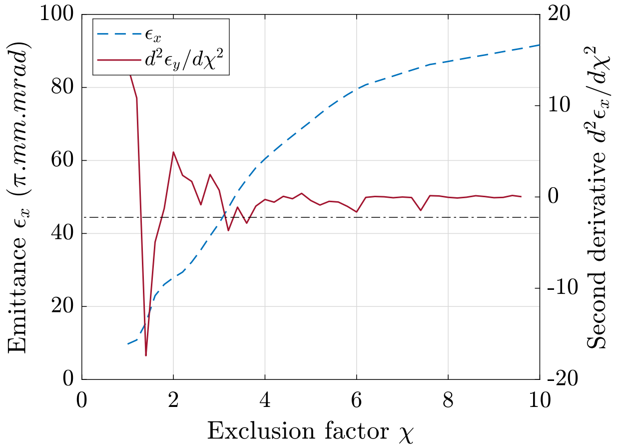

Figure 3: Determination of the exclusion factor χ, set here so that the absolute value of the second derivative of the emittance remains below of 2.5 a.u. (dash-dotted line).

RESULTS AND ANALYSIS

The results from the transverse beam properties measurements are listed in Table 1. We give more details about the ion source settings and beam parameters later. Because the first quadrupole of the triplet is set to shape the beam during the quadrupole scans and does not represent the typical operational focusing, we derive the Twiss parameters (β, γ) at the entrance of the triplet.

Several measurements of the transverse properties were carried out using a surface ion source. Measurements carried out in the HRS and GPS front-ends are consistent for this type of target. We choose to present the results of a uranium carbide target, with tantalum as surface ionizer (ISOLDE target 635). The target and line heating were I_{target} = 370 A and I_{line} = 220 A. The extraction electrode's position was set to nominal, so D_{puller} = 60 mm, at a voltage of U_{puller} = 30 kV. The beam was mainly composed of singly-charged potassium. The plasma ion source (ISOLDE target 734) was installed on the GPS frontend, with target and line heating at respectively I_{target} = 300 A and I_{line} = 420 A. The anode voltage was set to U_{anode} =130 V and the coil current to I_{magnet} = 5–6 A. The extraction electrode was positioned at D_{puller} = 120 mm, with U_{puller} = 30 kV. The pressure of gas mixture (noble gases) into the target was 1.1 bar. The LIST (ISOLDE target 634) was operated in ion guide mode with two repellers at -120 V and an RF amplitude of 60 V (peak-to-peak) at 704 kHz. The target and line heating were set for I_{target} = 650 A and I_{line} = 300 A. The puller distance from the target was D_{puller} = 145 mm, with U_{puller} = 50 kV.

The results are now compared with a previous series of measurement using a commercial emittance meter [6]. For a plasma ion source, the emittance was measured to be at a minimum of $\epsilon(4-\text{rms})$ = 8–10 π.mm.mrad for a 30 kV/u beam of I_{total} = 1–3 μA when optimizing the extraction electrode position, at D_{puller} = 88 mm. This value is significantly lower than the new measurement, which could be explained by the difference in the extraction electrode positioning. For a surface ionizer, the emittance was measured (still in [6]) to be $\epsilon(4-\text{rms})$ = 17–22 π.mm.rad for D_{puller} = 90 mm, U_{puller} = 30 kV and I_{total} = 0.5–3 μA. We show that the previous measurements are consistent with the new review of the emittance from surface ion sources.

Table 1: Summary of the Measured Transverse Beam Properties for Different Target Ion Sources

Type	Parameter	Value
Surface	$\epsilon_{x,y}$ (π.mm.mrad)	12 , 15 ±4
	$\beta_{x,y}$ (mm.mrad^{-1})	2.5 , 3.4 ±2.1
	$\gamma_{x,y}$ (mrad.mm^{-1}))	13 , 10 ±4.0
	I_{total} (nA)	0.6
	E (keV/u)	30
Plasma	$\epsilon_{x,y}$ (π.mm.mrad)	39 , 36 ±4
	$\beta_{x,y}$ (mm.mrad^{-1})	1.7 , 2.4 ±1.1
	$\gamma_{x,y}$ (mrad.mm^{-1})	8.6 , 5.5 ±2.5
	I_{total} (nA)	100
	E (keV/u)	30
LIST	$\epsilon_{x,y}$ (π.mm.mrad)	60 , 52 ±4
	$\beta_{x,y}$ (mm.mrad^{-1})	3.0 , 1.5 ±1.5
	$\gamma_{x,y}$ (mrad.mm^{-1})	2.9 , 4.6 ±1.9
	I_{total} (nA)	0.5
	E (keV/u)	50

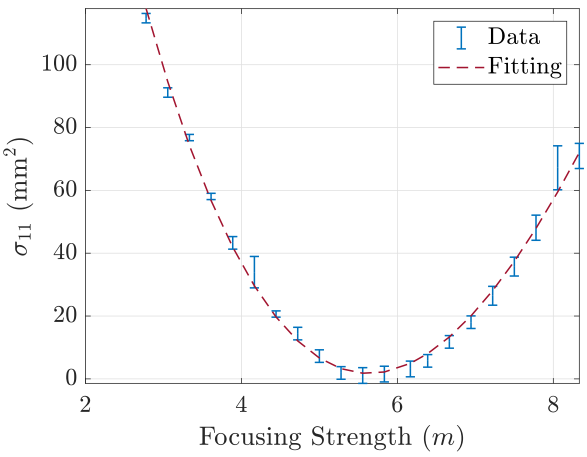

Figure 4: Example of the fitting obtained on the measured beam variances σ_{11} when varying the quadrupole's focusing.

CONCLUSION AND PERSPECTIVES

The quadrupole scan method presented with the experimental setup is deemed to be viable for measuring the transverse beam properties extracted from the ISOLDE ion sources. The error bars on the absolute values remain large, and it would be beneficial to correlate those measurements with another technique. With this perspective, an Allison scanner is currently under commissioning at ISOLDE.

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