BENCHMARKING OF MEASUREMENT AND SIMULATION OF TRANSVERSE RMS-EMITTANCE GROWTH ALONG AN ALVAREZ DTL

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Abstract

Transverse emittance growth along the Alvarez DTL section is a major concern with respect to the preservation of beam quality of high current beams at the GSI UNILAC. In order to define measures to reduce this growth appropriate tools to simulate the beam dynamics are indispensable. This paper is on benchmarking of three beam dynamics simulation codes, i.e. DYNAMION, PARMILA and PARTRAN against systematic measurements of beam emittance growth for different machine settings. Experimental set-ups, data reduction, the preparation of the simulations, and the evaluation of the simulations will be described. It was found that the mean value of final horizontal and vertical rms-emittance can be reproduced well by the codes.

INTRODUCTION

In the last decades many beam dynamics computer codes were developed [1] in order to simulate emittance growth along a linac. Several benchmarking studies among codes have been performed [2, 3, 4] generally assuming idealized conditions as initial Gaussian distributions, equal transverse emittances, matched injection into a periodic lattice, and small longitudinal emittance with respect to the rf-bucket size. In case of an operating linac most likely non of these conditions is met. To apply simulation codes to a realistic environment a benchmark activity was started aiming at the simulations of beam emittance measurements performed at a DTL entrance and exit, respectively. The studies were performed at the GSI UNILAC [5]. For the simulations three different codes were used: DYNAMION [6], PARMILA (V 2.32) [7], and PARTRAN [8]. A more detailed description of the campaign is given in [9].

EXPERIMENT SET-UP AND PROCEDURE

Intense beams are provided by MEVVA, MUCIS, or CHORDIS sources at low charge states with the energy of 2.2 keV/u. An RFQ followed by two IH-cavities (HSI section) accelerates the ions to 1.4 MeV/u using an rf-frequency of 36 MHz. A subsequent gas-stripper increases the average charge state of the ion beam. Final acceleration to 11.4 MeV/u is done in the Alvarez DTL section operated at 108 MHz. The increase of rf-frequency by a factor of three requires a dedicated matching section preceding the DTL. It comprises a 36 MHz buncher for longitudinal bunch compression, a 108 MHz buncher for final bunch rotation, a quadrupole doublet for transverse compression, and a quadrupole triplet for final transverse beam matching.

The Alvarez DTL comprises five independent rf-tanks. Transverse beam focusing is performed by quadrupoles in the F-D-D-F mode. Each drift tube houses one quadrupole. The periodicity of the lattice is interrupted by four intertank sections, where D-F-D focusing is applied. Acceleration is done -30^o from crest in the first three tanks and -25^o from crest in the last two tanks.

Figure 1 presents the schematic set-up of the experiments. Beam current transformers are placed in front of

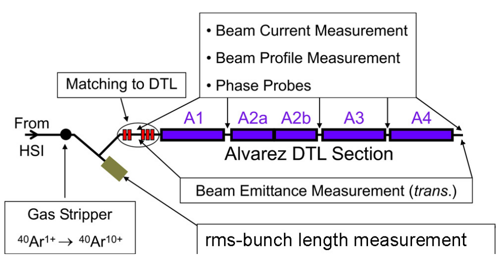

Figure 1: Schematic set-up of the experiments.

and behind the DTL as well as horizontal and vertical slit/grid emittance measurement devices. The total accuracy of each rms-emittance measurement including its evaluation is estimated to be 10%. A set-up to measure the longitudinal rms-bunch length is available in front of the DTL [10]. It measures the time of impact of a single ion on a foil. This time is related to a 36 MHz master oscillator. The resolution is 0.3° (36 MHz).

The HSI was set to obtain 7.1 mA of $^{40}Ar^{10+}$ in front of the DTL being space charge equivalent to the UNILAC design beam of 15 mA of $^{238}U^{28+}$. Horizontal and vertical phase space distributions were measured in front of the DTL. The longitudinal rms-bunch length was measured at the entrance to the DTL. The DTL quadrupoles were set to zero current transverse phase advances σ_o ranging from 35° to 90° in steps of 5°. Due to space charge the phase advances in all three dimensions were depressed. The transverse depression reached from 21% (90°) to 43% (35°). Afterwards the quadrupoles and bunchers preceding the DTL were set to obtain full transmission and to minimize low energy tails of the beam. For each value of σ_o horizontal and vertical beam emittances were measured at the exit of the DTL with a resolution of 0.8 mm in space and 0.5 mrad in angle.

Each emittance measurement delivers a two dimensional matrix of discrete slit-positions and discrete angles. The data are processed by the measurement & evaluation program PROEMI [11]. Fractional emittances can be extracted as well since in practical cases it is beneficial to focus on the ”inner” 95% of the particles. The emittance containing a given percentage p of the full distribution is extracted as follows: (i) The sum $\sum_{100}$ of all pixel contents is calculated. (ii) The pixels are sorted by their content starting from the largest one. (iii) Starting from the largest content the sum of all pixel contents is built as long as this sum is less or equal to the percentage p of $\sum_{100}$. (iv) Those pixels that contributed to the sum are considered for the rms-evaluation. Simulation deliver a set of six dimensional particle coordinates. This ensemble is projected onto a pixel-grid having the same characteristics as the slit/grid device used for the measurements. The grid is read by the measurement evaluation program PROEMI such that data reduction was done in the same way as for measured data.

INPUT FOR SIMULATIONS

From the transverse emittances measured in front of the DTL normalized 100%-rms-emittances of 0.12 and 0.23 mm mrad were evaluated horizontally and vertically, respectively. Measuring the rms-bunch length in front of the DTL a value of 25 mm was found corresponding to a phase spread of 20° at 36 MHz.

The reconstruction of the initial distribution is done in two steps. First the 100%-rms-Twiss parameters are determined. In the second step the type of distribution is reconstructed. The transverse rms-measurements and the longitudinal rms-measurements on the initial distribution, done at different locations along the beam line (Fig. 2), had to be combined.

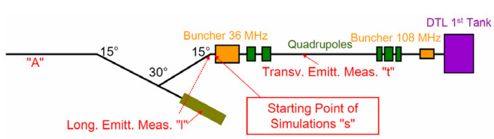

Figure 2: Reference points used for reconstruction of the initial phase space distribution.

This was achieved by attaching to the transverse rms-parameters measured at location “t” such longitudinal rms-parameters that result in the measured rms-bunch length measured at location “l”, after rms-tracking the distribution from “t” to “s”. The tracking implies the assumption that the virtual transport from “l” to “s” can be approximated by a simple drift including space charge. The length of this drift is given by the difference of the distances (“A”, ”l”) and (“A”, ”s”), i.e. 0.4 m. Additionally, the recombined distribution must result in longitudinally matched injection into the DTL in accordance with the measurements. Eventual longitudinal mismatch could have been observed experimentally by transmission loss and the occurance of low energy tails.

The reconstruction of the type of distribution is based on evaluation of the brilliance curve, i.e. the fractional rms-emittance as function of the fraction (Fig. 3). Different

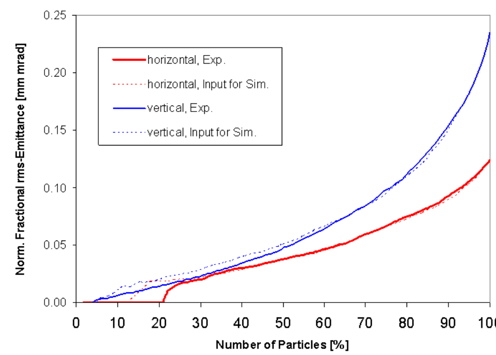

Figure 3: Brilliance curves of the phase space distribution in front of the DTL. Bold: from measurement; dashed: from initial distribution for simulations

amounts of halo have been found in the two transverse planes as indicated by the horizontal and vertical curvatures. For proper modelling of the initial distribution, both curvatures must be reproduced. This was achieved by using a distribution function as

$$f(R) \;=\; \frac{a}{2.5\cdot 10^{-4} \,+\, R^{10}}, \quad R \leq 1 \qquad (1)$$

and $f(R)$=0 for $R > 0$ with

$$R^2 \;=\; X^2 + X'^2 + Y^{1.2} + Y'^{1.2} + \Phi^2 + (\delta P/P)^2 \,, \quad (2)$$

where a is the normalization constant and the constant in the demoninator results from the cut off condition at R = 1. By defining the radius R using different powers for different sub phase spaces the halos within the planes could be modelled. Since for the longitudinal phase space distribution no measurement but on the rms-bunch length is available, a Gaussian distribution cut at 4σ is assumed. This can be achieved by setting the respective powers in the definition of R to a value of 2.

COMPARISON OF RESULTS

For all phase advances full beam transmission was observed through the DTL in the experiment. The codes revealed losses of about 2%. Figure 4 displays final horizontal phase space distributions at the DTL output as obtained from measurements and from simulations for three different values of σ_o. The simulated final distributions look quite similar. Simulations could reproduce the wings attached to the core measured at highest phase advances. But the codes did not show the asymmetric distributions measured at lowest phase advances. Final 95%-rms-emittances

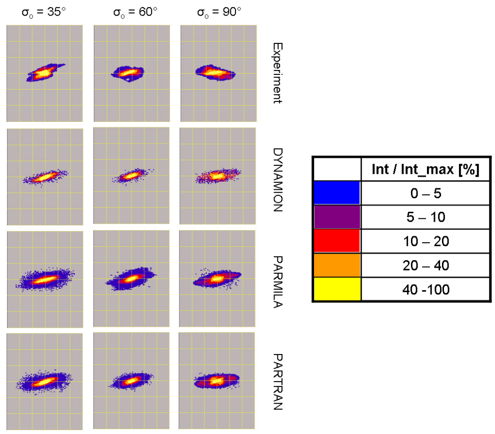

Figure 4: Top to buttom: horizontal phase space distributions at the DTL exit. Left: σ_o = 35°; centre: σ_o = 60°; right: σ_o = 90°. The scaling is ± 24 mm (horizontal axis) and ± 24 mrad (vertical axis), respectively.

are presented in Fig. 5 to Fig. 7 as function of the transverse phase advance σ_o. The measurements and the simulations revealed lowest emittances at $\sigma_o \approx 60°$. In general good agreement among the codes was found. However, the codes slightly underestimate the emittance growth. This is reasonable since the codes assume a machine without errors causing additional growth [12].

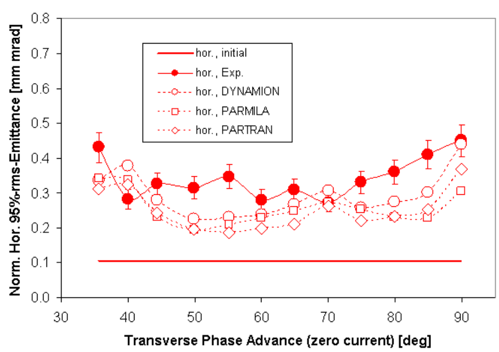

Figure 5: Horizontal 95%-rms-emittance at the end of the DTL as function of σ_o.

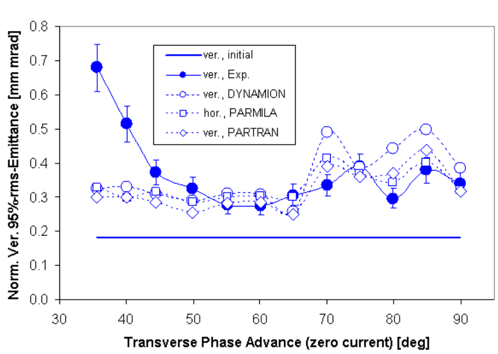

Figure 6: Vertical 95%-rms-emittance at the end of the DTL as function of σ_o.

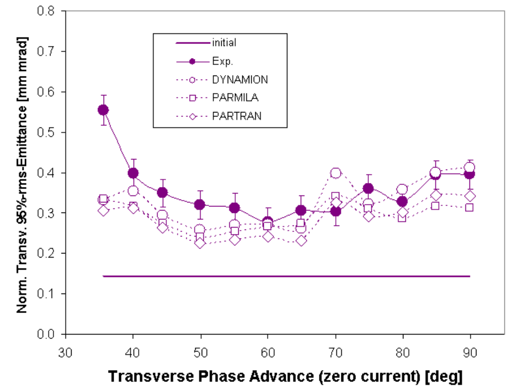

Figure 7: Mean value of horizontal and vertical 95%-rms-emittance at the end of the DTL as function of σ_o.

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