BEAM DYNAMICS SIMULATION OF THE 1.5 MEV PROTON BEAM MEASURED AT THE SARAF RFQ EXIT

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Abstract

The Soreq Applied Research Accelerator Facility (SARAF) beam dynamics simulations are compared to the first beam measurements taken during commissioning. Beam transmission, ion energy and bunch width as functions of the RFQ power have been measured. The simulations and measurements show similar trends. The simulation covers the beam tail as well and is used to find the optimal operating voltage by minimizing the low energy tail and beam loss downstream the accelerator.

INTRODUCTION

The SARAF linac [1] front-end is composed of a 20 keV/u protons and deuterons ECR ion source, a 5 mA low energy beam transport (LEBT) [2] and a 1.5 MeV/u, 4 mA, 176 MHz, 4-rod RFQ [3] (Fig.1).

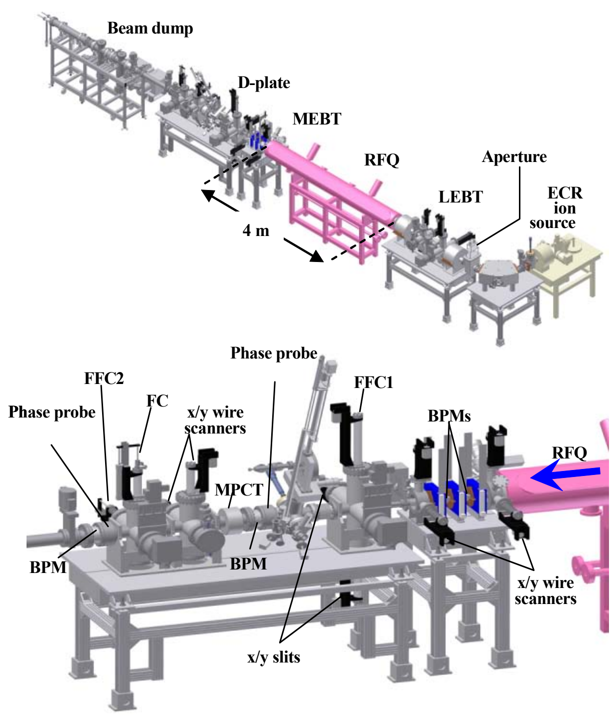

Figure 1: Top: the SARAF linac front-end setup, as used for the protons beam measurements and simulations in this paper. Bottom: the location of the diagnostic devices downstream the RFQ that were used. BPM- beam position monitor, FFC- fast Faraday cup, MPCT- modular parametric current transformer.

In this work, beam dynamics simulations of the front-end are compared to the first proton beam measurements taken during commissioning [2]. Beam transmission, ion energy and bunch width as a function of the RFQ power have been measured in the medium-energy beam transport (MEBT) diagnostics and using a dedicated diagnostic plate (D-plate) (Fig.1). The similar trend between simulations and measurements allows calibrating the RFQ power to its electrodes voltage, in the low electric field range, where the common X-ray measurement method is not feasible. The RFQ is designed as a deuteron accelerator and therefore is potentially capable of producing four times the power needed for accelerating protons. This enables us to measure the RFQ proton beam properties, not only up to the optimal power, but also in a wide range above the optimal power.

Even though measurement devices are usually limited to the beam core, due to the detection techniques sensitivity and resolution, the simulation in this work covers the beam tails as well. All beam dynamics simulations presented in this work were performed using the TRACK code [4].

SETUP FOR BENCHMARK

Typical 5 mA proton beams are analyzed and measured in the LEBT emittance apparatus and show an rms normalized transversal emittance of 0.15 π·mm·mrad at the location of measurement [5]. For the measurement described here the beam current was reduced to 3 mA (instantaneous current). The LEBT beam optics was simulated starting downstream of the ion source extraction electrodes with a 4D Waterbag distribution and normalized to generate an emittance of 0.15 π·mm·mrad at the LEBT slit and wire position. We assume a beam waist at the ion source exit.

In order to match the beam to the RFQ and reach maximum transmission, the LEBT stirrers were used in the measurement. In the simulation the solenoids were operated with magnetic fields as similar as possible to the measurements values, but steerers were not included. The beam was operated in a pulse mode in order not to exceed the diagnostic rated power of 200 W. The ion source and the RFQ RF power supplies (PS) are pulsed as described in [2] in order to shape the ion pulses. The beam current was measured in the LEBT, upstream of the RFQ entrance, using a Faraday cup. Downstream of the RFQ, the beam current was measured using the MEBT BPM sum signal and using the calibrated Bergoz MPCT at the D-plate (Fig.2). Ion energy was extracted from time-of-flight measurements between the two MEBT BPMs, used as phase probe pickups, and confirmed by a measurement in additional two phase probes at the D-plate [2]. The longitudinal bunch width was measured by Fast Faraday cups (FFCs) located 1.064 m and 2.649 m downstream the RFQ exit flange. The transversal beam profile was measured using a set of x/y wire scanners [2].

RESULTS

Comparison between the simulated and measured beam current as a function of the RFQ power is presented in Fig.2. The simulation predicts well the BPM signal trend at operating voltage. However, the current value of the BPM is not calibrated. Similar trends are found in the SNS and ISIS RFQs measurements and simulations [6,7,8]

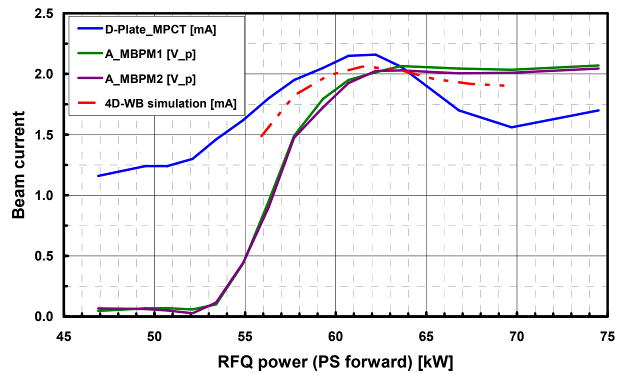

Figure 2: Proton beam current, as function of the RFQ PS power, measured using the MPCT (blue) and the MEBT BPMs (green and violet). The red dashed curve presents the current predicted in the simulation peaked at 32.0 kV estimated as 61.5 kW.

The MPCT current measurements presented in Fig.2 include unsynchronised particles at low power not included in the BPM bunch measurement. The drop measured at high power at the D-plate might be due to beam loss in the D-plate. This assumption is supported by the measured wire scanner profiles in the D-plate current measurements as function of the RFQ power.

When using LEBT operating conditions, the maximum transmission in the simulation is limited to ~70% similar to the measured transmission; this transmission is attributed to the beam mismatch at the RFQ entrance. For optimal matching the simulated transmission is 96%. In the measurement, the transmission might be also limited due to misalignment found at this stage of the commissioning.

The proton energy predicted by the simulation is low at low electrode voltage, reaches the design value of 1.5 MeV at 30.0 kV and stays constant at higher voltages. Similar step-function behaviour was measured as a function of the RFQ power (fig.3). In the measurement, this designed proton energy is reached at a PS power of 55 kW. The match of the simulated and the measured energy "step-functions" predicts that the design voltage of 32.5 kV is reached at 63.5 kW without beam load. The RFQ is operated in a closed loop keeping a constant voltage and critical coupling without beam load. While the beam pulse loading the coupling is detuned with a negligible reflected power.

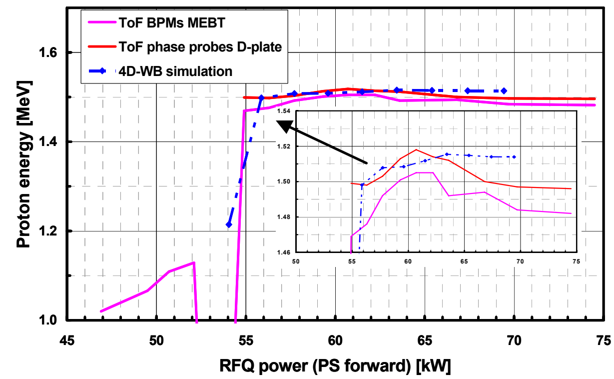

Figure 3: Proton energy as function of RFQ power, simulation vs. measurement. Inset: magnification of the energy rise to around 1.5 MeV.

The simulated and measured transverse profiles downstream the RFQ, at the MEBT entrance and at the D-plate are shown in Fig.4. The simulated and the measured longitudinal bunch profile at FFC1 are presented in Fig.5 for the optimal RFQ voltage/power. In these conditions the profile shape is a Gaussian with σ=10 deg.

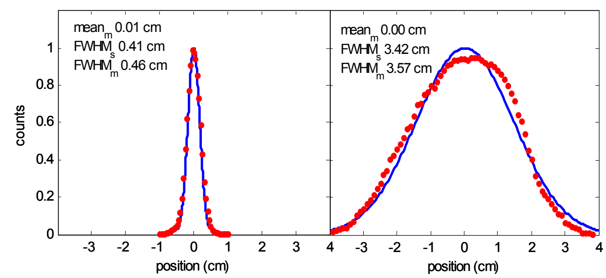

Figure 4: Transversal x beam profile at 32.0 kV in simulation (blue line) and in minimum measured bunch length at 61.5 kW (red dots) in the MEBT entrance (left) and D-plate (right).

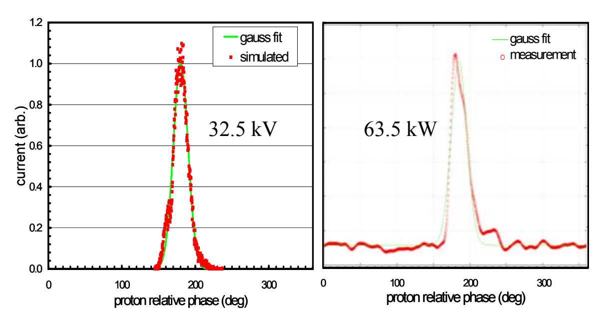

Figure 5: Proton time distribution inside a bunch at FFC1. Time is presented as degrees of 176 MHz (360 deg=5.68 ns). Left: simulation of one bunch with 40,000 macro-particles. Right: an average of 100 measured bunches, both taken at optimal RFQ voltage/power, where the bunch widths are similar.

The proton bunch width as function of the RFQ PS power is shown in Fig.6. There is a good agreement between the simulated and measured values at FFC1 and optimal RFQ power. At FFC2 and optimal RFQ power the simulated value is higher than the measured value. This is probably due to a smaller actually energy spread (not yet measured) than the energy spread found in the simulations. We simulated the fact that the FFC measures only a small fraction (<1%) of the beam at the beam center. The result shows that at optimal RFQ power, this effect introduces a maximum error of 10% in the estimated bunch length.

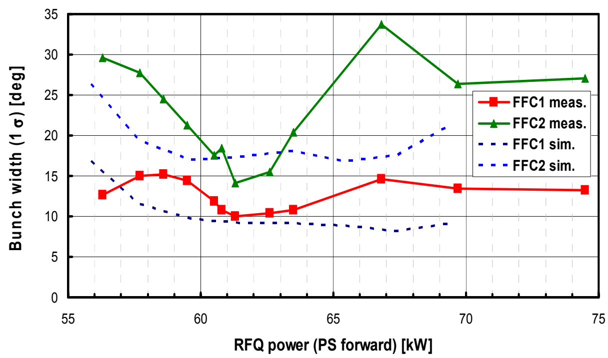

Figure 6: Proton bunch width as function of RFQ power measured in the D-plate FFCs (solid) and simulated at the location of the FFCs (dash). The width here is defined as one σ of a Gaussian fitted to the measured or simulated results, as shown in fig.5.

The optimum operating power region of the RFQ was evaluated, taking into account minimum expected beam losses, maximum transmission and a low operating electrode voltage. The minimization of the expected losses along the superconducting accelerator downstream of the RFQ is achieved in the simulation by eliminating the low-energy tail at the RFQ exit. This can be analyzed by minimizing the halo parameter defined in [9]. Our results show (Fig.7) that increasing the RFQ voltage above the design value will not improve significantly the beam quality. A similar analysis of the TRASCO RFQ is found in [10].

All the simulations presented above have been repeated using initial 4D Gaussian distributions at the ECR exit and gave similar output behaviour at the RFQ exit.

The beam measurements, with lower precision, have been performed also for an injected current of 0.5 mA and the simulations reported above have been repeated for this case. The high current 70% transmission goes up to 90% in a low current. The time and energy distribution does not present a typical Gauss shape but a double peak distribution is observed, due to the reduction of the space charge effect. This behaviour is explained by the low non linear space charge effects (needed to remix the distribution) and the larger separatix width in low current that enabled the beam to expand in longitudinal phase space [10]. The SARAF RFQ bunching and focusing strengths were optimized for deuterons at 5 mA [3]. In terms of the space charge effect, the optimal current for protons is then 2.5 mA.

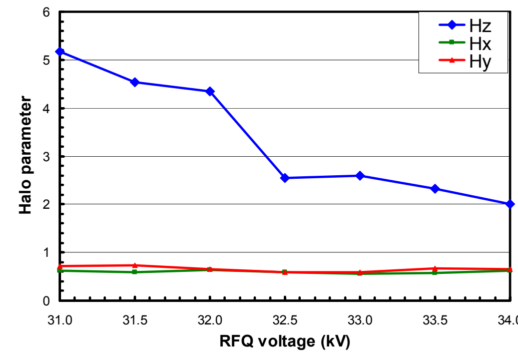

Figure 7: Simulated halo parameters as function of RFQ electrodes voltage in the longitudinal (upper blue) and transversal (red and green) phase spaces.

CONCLUSIONS

The benchmark between the simulation and measurement shows that the RFQ model in our simulation can predict well the measured values. The simulation is used for calibrating unknown parameters such as the electrode voltage and is used for understanding the measurements. There are still discrepancies between the simulation and the measurements that may be explained by misalignment inside and outside the RFQ, which is not taken into account in the simulation, and by the fact that the simulation starts with a Water Bag or Gaussian distribution at the ion source exit and not with a realistic distribution. These last differences can be improved after realignment and if the beam emittance is specifically measured at the LEBT at the matching condition to the RFQ, and the results will be processed to regenerate the simulation initial distribution.

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