STATUS OF THE END-TO-END BEAM DYNAMICS SIMULATIONS FOR THE GSI UNILAC

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Abstract

The heavy ion high current GSI linac UNILAC serves as an injector for the synchrotron SIS18. The UNILAC mainly consists of a High Current Injector (HSI), the stripper section at 1.4 MeV/u, and the Alvarez postaccelerator (11.4 MeV/u). During the last years the systematic experimental and numerical studies resulted in an increase of the U^{73+} beam intensity of up to a factor of seven. The needs of the FAIR project (Facility for Antiproton and Ion Research) at Darmstadt require further improvement of the UNILAC beam brilliance up to a factor of five. End-to-end beam dynamics simulations with the DYNAMION code have already been started. The general goal is to establish a simulation tool which can calculate the impact of the planned upgrade measures on the performance of the whole UNILAC. The results of the HSI calculations including influence of the beam intensity on the beam parameters (current, emittance, Twiss-parameters) at the stripper section are presented. Recent calculations and measurements of the beam matching to the Alvarez section under space charge conditions are discussed.

INTRODUCTION

The present GSI-accelerator complex consists of the UNIversal Linear ACcelerator UNILAC (Fig. 1) and the synchrotron SIS 18.

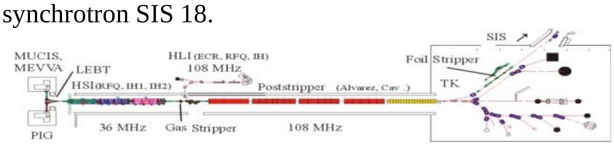

Figure 1: Schematic overview of the GSI UNILAC

It is foreseen to serve for the future synchrotron SIS 100 as an injector for up to 10^{12} U^{28+} particles/sec. For the international facility FAIR the present particle number in the SIS 18 has to be increased by more than two orders of magnitude [1].

THE GSI-UNILAC

The High Current Injector (HSI) of the UNILAC consists of ion sources (MEVVA-, MUCIS- or Penning-type); a low energy beam transport system (LEBT); the 36 MHz IH-RFQ accelerating the ion beam from 2.2 keV/u to 120 keV/u; the matching to the following IH-DTL with a short 11 cell adapter RFQ (Super Lens); the IH-DTL consisting of two separate tanks accelerating the beam up to the full HSI-energy of 1.4 MeV/u. Before injection into the Alvarez accelerator the HSI-beam is stripped and one charge state is selected (e.g. 28+ for uranium beams). The five tanks of an Alvarez type accelerate the high intensity HSI beam without any significant particle loss. In the transfer line to the SIS 18 at 11.4 MeV/u a foil stripper and another charge state separator system is in use. For the longitudinal matching to the SIS 18, the single gap resonators can be used, as well as a dedicated 36 MHz-rebuncher in the transfer channel (TK) to the synchrotron .

Since 1999, when the HSI had been commissioned, many different ion species were accelerated in routine operation. The measured U^{73+} beam current at the SIS 18 entrance was increased from 0.3 emA in 2001 up to 2.0 emA in 2003. Newertheless for the recent design up to 4.6 emA of an U^{73+} or 12 emA of an U^{28+} should be delivered; requirements for FAIR are even higher (15 emA of an U^{28+}) [2].

Several measures are planned for the UNILAC upgrade to reach the FAIR requirements:

- front-end system including new LEBT and RFQ;
- new gas stripper box;
- new quadrupole lenses in Alvarez postaccelerator;
- new charge state separator in the TK;
- advanced beam diagnostics.

Therefore end-to-end simulations for the whole linac (from ion source output to the synchrotron entrance) are required for the study and optimization of the overall machine performance as well as for the calculation of the expected impact of different upgrade measures, proposed to improve the intense beam brilliance.

EARLIER CALCULATIONS

For the earlier end-to-end simulations of beam dynamics in the different accelerator sections of the UNILAC the codes PARMT, PARMTEQ, LORASR and PARMILA were used [3]. The transfers of the particle coordinates between the codes with different conversation units were required. Calculations were done for 15 emA of an uranium beam current and showed dramatic result: just about of 50% of the intensity, delivered to the synchrotron entrance, fits to its acceptance. Furthermore one has to take into account that the well-known codes of the PARMILA-family don't provide the high accuracy of the calculations due to their intrinsic simplifications: paraxial approximation for the particle motion, analytical calculations of the external field, and the insufficient representation of the space charge effects. Therefore an implementation of a more reliable code for the UNILAC end-to-end simulations is required.

RECENT CALCULATIONS

With the advanced multiparticle code DYNAMION [4] it is possible to calculate beam dynamics in linear accelerators and transport lines under space charge conditions with high accuracy and reliability. This is reached by an improved description of the external and internal fields inside the code and use of the data from measurements or from calculations performed with external codes (e.g. focusing and accelerating fields, beam emittance, misalignments, etc.). Generally, particle motion in the whole linac, potentially consisting of RFQs, DTLs and transport lines, can be calculated in one run. Step by step simulations of the linac parts and transition of the obtained particle distribution to the following sections are also available with the same reliability.

HSI-RFQ upgrade 2004

An impressive application of the DYNAMION power was the beam dynamics study for the upgrade of the HSI-RFQ in 2004 [5]. The RFQ was completely dismounted and new electrodes with higher quality of surface were fabricated. The main goal - the reduction of the rf power required for the acceleration of the heavy ion beams - was achieved. Additionally, the RFQ Input Radial Matcher (IRM) was redesigned to improve the beam transmission through the whole front-end system. The DYNAMION calculations predicted an intensity gain of up to 15% for high current uranium beam (15 emA) perfectly confirmed by measurements [6].

High current injector

The beam dynamics in the High Current Injector were simulated in the frame of the end-to-end calculations of the UNILAC with the multi-particle code DYNAMION. As a first step, an adequate description of the HSI elements has been carried out. All geometrical data, available from the specifications and drawings for the machining, were used: length of elements, apertures, width and rounding of the RFQ electrodes, inner and outer rounding of the DTL tubes, etc. Gradients for the magnetic quadrupole lenses have been obtained from the machine settings, established manually during operation with high current U^{4+} beam. The voltage in each gap of IH-1 and IH-2 tanks has been obtained from bead-pull measurements. Dedicated subroutines of the DYNAMION code precisely calculate the 3D external electrical field solving the Laplace equation for potential:

- *Input Radial Matcher:* the area for the grid is formed by the surface of electrodes / flange of the tank; data are introduced into calculations as field mapping.
- *RFQ cells:* the area for the grid is formed by the surface of the modulated electrodes; potential and 3D electrical fields for each cell are approximated with classical 8-term series assuming the quadrupole symmetry; coefficients of the series are introduced into calculations as input data.
- *DTL gaps:* the area for the grid is formed by the surface of tubes; potential and 3D electrical fields for each gap, including slack of the field into tubes, are approximated with 30-term series assuming axial symmetry; coefficients of the series are introduced into calculations as input data.

A Gaussian (truncated at 2σ) input distribution of an U^{4+} particle at the RFQ entrance has been generated in both transverse planes; uniform in the longitudinal one. Matched Twiss-parameters at the RFQ entrance have been calculated for an unnormalized beam emittance of 208 mm*mrad and a beam current of 15 emA. These values correspond to the measurements in the LEBT.

Beam dynamics simulations in the whole HSI have been done with different beam currents taking space charge forces into account. The method of the particle-particle interaction was implemented; a dedicated routine prevents artificial particle collisions. Virtual bunches (before and after the main one) are introduced for an adequate calculation of the space charge influence for the continuous beam concerning the bunching process in an RFQ.

Misalignments of the RFQ electrodes were not included into the recent calculations (generally it is possible). This fact, together with artificial input distribution of particles, matched to the RFQ input, allows to treat results of simulations as upper limit of the HSI performance with given beam parameters. The beam phase space portraits behind the HSI for the input current of 15 emA are shown on the Fig. 2. The output beam current is 11 emA.

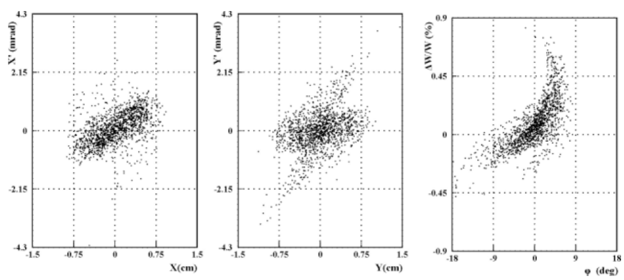

Figure 2: Calculated beam phase space portraits (11 emA) behind HSI; the input U^{4+}beam current is 15 emA.

Calculations, done with different input beam currents, are summarized in Fig. 3. Beam brilliance inside unnormalized emittance of 10 mm*mrad (design value for FAIR) is shown as a function of the input beam current.

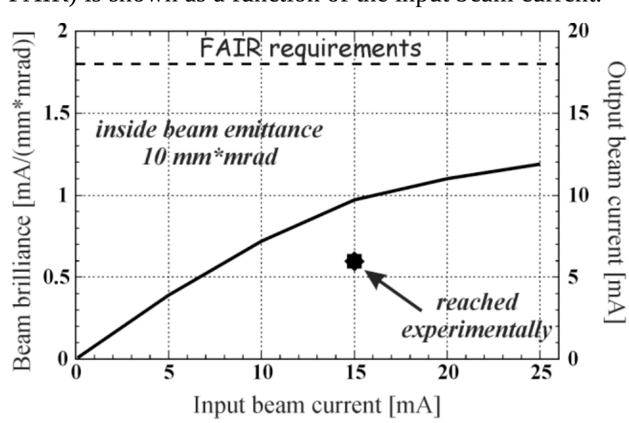

Figure 3: Output beam -brilliance (left scale) and -current (right scale) calculated inside output emittance of 10 mm*mrad (FAIR requirements) as a function of the input current at the RFQ entrance.

Additionally, the experimentally reached brilliance is shown. As one can see, even the upper limit, which can be theoretically achieved, is significantly lower than the FAIR requirements. For this reason the general upgrade of the front-end system including a completely new -LEBT and -RFQ is mandatory.

Gas stripper and matching section to the Alvarez poststripper accelerator

Before injection into the Alvarez accelerator the HSI-beam is stripped and one charge state is selected (e.g. 28+ for uranium beams). For the simulations of the space charge dominated beam dynamics in this section the measured spectra of the charge states will be used.

Preceding the Alvarez DTL there is the section comprising five quadrupoles and two bunchers to provide a matched injection. The section includes a slit/grid set-up to measure the transverse emittances. The longitudinal beam emittance can be measured with a dedicated device [7]. A dedicated rms-matching code [8], based on emittance measurements in between the quadrupoles, was realized and applied during machine experiments. For a given set of beam parameters and a given setting of the DTL quadrupoles it provides the optimized settings of the five quadrupoles and the two bunchers. For transverse matching this procedure was already verified experimentally [9] and it is foreseen to implement it to the beam dynamics simulations in the same manner. 3-D particle coordinates at the position of emittance measurements can be easily extracted from the DYNAMION output file.

Alvarez poststripper accelerator and Transfer Channel to the SIS 18

As an example of the simulated results, the horizontal beam -envelope and -emittance along five Alvarez tanks (including inter-tank sections) are shown in Fig. 4. Preliminary beam dynamics simulations with artificial particle distribution were done for an Ar^{10+} beam intensity of 7 emA corresponding in terms of space charge to the design value of 15 emA for U^{28+} beam current.

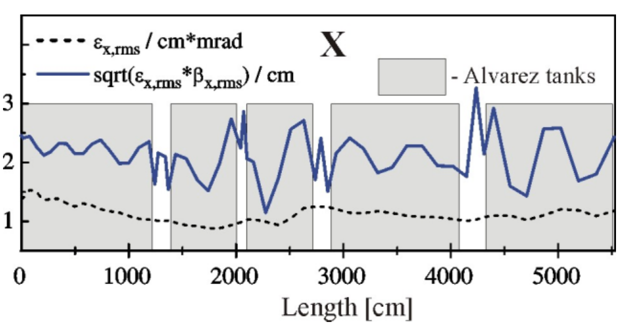

Figure 4: Horizontal beam -emittance (rms, unnormalized) and -envelope along the Alvarez DTL, calculated with the DYNAMION code.

Beam dynamics simulations in the transfer channel to the synchrotron including charge separation after the foil stripper are foreseen in the nearest future.

CONCLUSION

An end-to-end simulation for the whole linac is an advanced tool for the study and optimization of the overall machine performance as well as for the calculation of the expected impact of different upgrade measures. The beam dynamics simulations by means of the DYNAMION code were carried out. Recently the HSI was under investigation. Several important results are already obtained:

- results, simulated by the DYNAMION code, are successfully verified during machine experiments;
- for high current U^{4+} beam the HSI output current is limited to12 emA;
- a bottle-neck of the whole HSI is the RFQ which has to be redesigned for the FAIR needs (18 emA inside design emittance of 10 mm*mrad);
- additionally a completely new front-end system [10] is necessary to match the uranium beam to the RFQ.

Further beam dynamics simulations for the stripper section, the Alvarez postaccelerator and the transfer channel to the synchrotron will be done consequently using particle distribution coming from the HSI. Most of the data files are already prepared as well as a dedicated procedure for beam matching to the Alvarez tank.

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