IMPLEMENTATION OF THE DYNAMION CODE TO THE END-TO-END BEAM DYNAMICS SIMULATIONS FOR THE GSI PROTON AND HEAVY ION LINEAR ACCELERATORS

S. Yaramyshev*, W. Barth, L. Dahl, L. Groening, B. Schlitt GSI, Darmstadt, Germany

Abstract

The advanced multi-particle code DYNAMION is sufficient to calculate beam dynamics in linear accelerators and transport lines under space charge conditions with high accuracy. Special features like the consideration of field measurements, misalignment and fabrication errors, and data from the real topology of RFQ electrodes, drift tubes, quadrupole lenses lead to reliable results of the beam dynamics simulations. End-to-end simulations for the whole linac (from ion source extraction to the synchrotron entrance) allow for the investigation and optimization of the overall machine performance as well as for the calculation of the expected impact of different upgrade measures, proposed to improve beam brilliance. Recently the DYNAMION code is applied to investigate the beam dynamics for the different GSI-linacs: the heavy ion high current UNILAC, the high current proton linac for the future Facility for Antiproton and Ion Research at Darmstadt (FAIR), and the light ion accelerator for the cancer therapy (HICAT), to be commissioned in Heidelberg (Germany) in the near future. Recent results of the beam dynamics simulations by means of the DYNAMION code are presented. The proposed upgrade measures as well as tuning and optimization of the linacs are discussed.

INTRODUCTION

The versatile multiparticle code DYNAMION [1] was created in ITEP and developed in GSI. With the code 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, as well as the use of the data from measurements or from calculations performed with external codes (e.g. focusing and accelerating fields, beam emittance, misalignments, etc.). Generally, the 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 sections and transitions of the obtained particle distribution to the following sections are available with the same reliability.

An intense beam dynamics simulation is performed taking space charge forces into account. The method of particle-particle interaction is implemented; a dedicated routine prevents artificial particle collisions. Virtual bunches (before and after the main bunch) are introduced for an adequate calculation of the space charge influence for the continuous beam, the bunching process in an RFQ, and the behavior of the sequence of the bunches.

As a first step, an adequate description of the linac elements has to be carried out. All geometrical data, available from the external calculations, measurements, specifications and tables for the machining, can be used: cell length, aperture, width and rounding of the electrodes for an RFQ; tube and gap length, aperture, and tube rounding for a DTL. Dedicated subroutines of the DYNAMION code precisely calculate the 3D electrical field solving the Laplace equation for the potential:

RFQ Input Radial Matcher: the area for the grid is formed by the surface of electrodes / flange of the tank.

RFQ cells: the area for the grid for each cell is formed by the surface of the modulated electrodes; the potential is approximated with a classical 8-term series assuming the quadrupole symmetry; coefficients of the series are introduced into calculations as input data; 3-D electrical fields are calculated as corresponding derivatives of the potential.

DTL gaps: the area for the grid is formed by the surface of tubes; the potential and the 3D electrical fields for each gap, including the 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.

The transport line elements (quadrupole lenses, bending magnets, solenoids, etc.) are implemented inside the code or can be represented by measured or calculated field mapping. Several additional features are developed for more reliable simulations: apertures, beam shift and rotation, breeding of particles, etc.

The misalignments of the linac elements can be defined for the simulations.

Input particle distribution of several types (KV, truncated Gaussian, uniform, etc.) are available. The results of beam dynamics simulation performed by any tracking code can be transformed to the input data for the calculation of the following structures. The data of an emittance measurement can be used for generating of the input particle distribution which includes non-uniformities of a real beam.

A mixture of ions with a different charge, mass, or energy is usually delivered by an ion source. DYNAMION simulations can be carried out under space charge conditions using adequate multi-particle distributions. The stripping of ions to higher charge states increases the beam current on several times and leads to a wide spectrum of ion species with different charge to mass ratios. DYNAMION is able to calculate the behavior of the space charge dominated beam in a special section for the charge separation using a theoretical or measured charge states distribution.

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*s.yaramishev@gsi.de

RECENT RESULTS OF THE BEAM DYNAMICS SIMULATION

GSI Heavy Ion High Current UNILAC

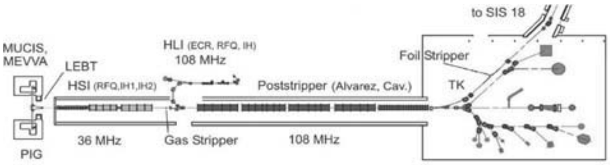

Fig. 1 Schematic overview of the GSI UNILAC

The present GSI-accelerator complex consists of the UNILAC (Fig. 1) and the synchrotron SIS 18. For the international facility FAIR the UNILAC particle number for the SIS 18 has to be increased by more than factor of three [2] to serve for the future synchrotron SIS 100 as an injector for up to 10^{12} U^{28+} particles/sec.

The High Current Injector (HSI) of the UNILAC consists of two ion source terminals (MEVVA-, MUCIS- and Penning-type); a low energy beam transport system (LEBT); a 36 MHz IH-RFQ accelerating the ion beam from 2.2 keV/u to 120 keV/u; a short 11 cell adapter RFQ (Super Lens); an 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 Alvarez type accelerate the high intensity HSI beams without significant particle loss up to 11.4 MeV/u. In the transfer line to the SIS 18 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. Since 1999, when the HSI had been commissioned, many different ion species were accelerated in routine operation. The measured U^{73+} beam current was increased from 0.3 emA (2001) up to 2.0 emA (2003). Nevertheless 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+}) [3].

The ability of DYNAMION as a powerful simulation tool was approved by the beam dynamics study for the upgrade of the HSI-RFQ in 2004. With the code an intensity gain of up to 15% for a high current uranium beam (15 emA) was predicted and confirmed by measurements [4].

Recently a dedicated upgrade program is planned for the UNILAC to fulfill the FAIR requirements:

- front-end system including new LEBT and RFQ;
- gas stripper box with increased aperture;
- increased field of the quadrupoles in the Alvarez tanks;
- new charge state separator in the TK;
- advanced beam diagnostics.

End-to-end simulations have to be performed to establish a tool suitable to calculate the impact of the planned upgrade measures on the performance of the whole UNILAC. An adequate description of the HSI elements had been carried out using all geometrical data, available from the technical specifications and drawings for the machining. Gradients for the magnetic quadrupole lenses had been obtained from the machine settings, established manually during operation with high current U^{4+} beams. The voltage in each gap of IH-1 and IH-2 tanks had been obtained from bead-pull measurements. A Gaussian input distribution (truncated at 2σ) of an U^{4+} beam had been generated in both transverse planes; uniform in the longitudinal plane. Matched Twiss-parameters at the RFQ entrance were calculated for an unnormalized beam emittance of 208 mm*mrad and a beam current of 15 emA, corresponding to the LEBT measurements.

The misalignments of the RFQ electrodes are not included into the recent calculations; only an artificial input particle distribution, matched to the RFQ was used. The presented HSI-beam performance (12 emA of U^{4+}) is calculated as an upper limit with given beam parameters.

The FAIR requirement to the U^{4+} beam current behind the HSI is 18 emA inside of the unnormalized beam emittance of 10 mm*mrad. The results of the HSI-beam dynamics simulations, performed with different input beam parameters, are summarized in Fig. 2. The output beam brilliance (inside the design emittance) is shown as a function of the input beam current. Additionally, the experimentally reached current is shown. As shown, even the theoretical limit is significantly lower than the FAIR requirements. A bottle-neck of the whole HSI is the RFQ. The general upgrade of the front-end system, including a completely new -LEBT and -RFQ, is mandatory [5].

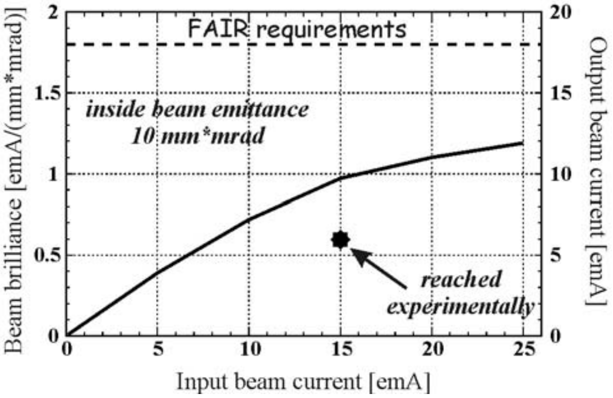

Fig. 2 Calculated output beam -brilliance (left scale) and -current (right scale) inside a design emittance of 10 mm*mrad as a function of the RFQ input current.

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. A dedicated procedure for beam matching to the Alvarez tank was already verified experimentally for low and medium current [6]. It is foreseen to implement it to the beam dynamics simulations in the same manner. As an example, the horizontal beam -envelope and -emittance along five Alvarez tanks (including intertank sections) are shown in Fig. 3. Preliminary beam dynamics simulations with an artificial particle distribution were done for an Ar^{10+} beam intensity of 7 emA. In terms of space charge it corresponds to the design U^{28+} beam current of 15 emA.

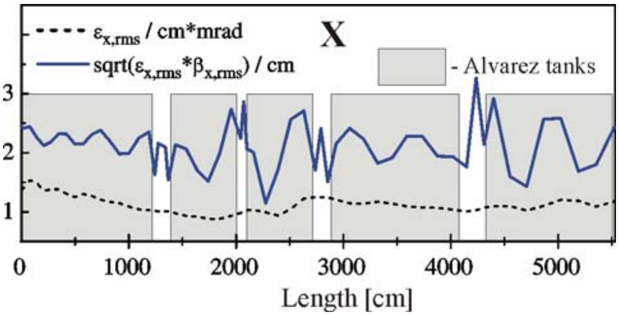

Fig. 3 Calculated horizontal beam -emittance (rms, unnormalized) and -envelope along the Alvarez DTL.

GSI High Current Proton Linac

The antiproton physics program for FAIR is based on a rate of $7 \cdot 10^{10}$ cooled antiprotons per hour. To provide the required primary proton beam a separate linac is developed recently and it will serves the facility as an injector [7]. The p-linac comprises a 100 mA proton source, an RFQ, a normal conducting Crossed-bar H-cavities DTL and a transfer line to the SIS 18 (Fig. 4).

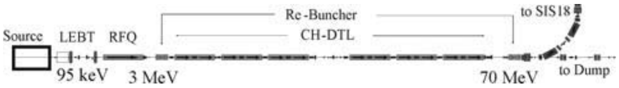

Fig. 4 Schematic view of the GSI proton linac.

The Institute for Applied Physics (IAP, Frankfurt University) and the Institute for Theoretical and Experimental Physics (ITEP, Moscow) propose two RFQ designs. Both RFQ designs have similar main parameters, namely length, voltage, average aperture etc. but differ significantly in the laws of modulation and synchronous phase along the structure [8, 9].

An adequate comparison of the RFQ designs [10] was done using the DYNAMION code. Therefore beam dynamics for the both designs were simulated solving the same particle motion equation under space charge conditions. The same input beam characteristics were used except matched Twiss-parameters.

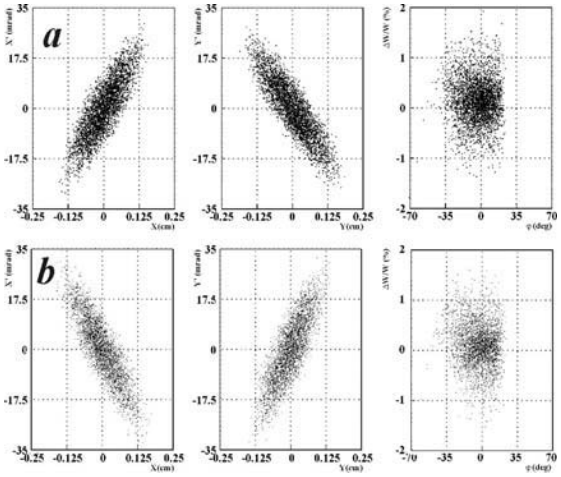

Fig. 5 Output phase-space particle distributions for the IAP (***a***) and ITEP (***b***) RFQ designs.

Results of the beam dynamics simulations for the RFQ designs are similar due to the particle transmission and the rms beam emittances. The output transverse and longitudinal phase space distributions of the particles are shown in Fig. 5.

Further beam dynamics simulations for the RFQ designs are foreseen including fabrication errors, misalignments, beam mismatching as well as realistic input particle distributions measured [11] or calculated by external code KOBRA [12]. The obtained particle distributions behind the RFQ will be used for the consequent beam dynamics simulations for the main part of the linac and the transfer line to the SIS18.

Linac for the Cancer Therapy Facility (HICAT)

The injector linac of the Heidelberg ion beam therapy center (Fig. 6) is currently in the commissioning phase [13]. Its main components are two electron cyclotron resonance ion sources, a 216 MHz RFQ and an interdigital H-type drift tube structure. The linac is able to accelerate beams of hydrogen-, helium-, carbon- and oxygen-ions up to energy of 7 MeV/u. The accelerator beam lines and structures have been designed under the leadership of GSI with contributions of the IAP Frankfurt.

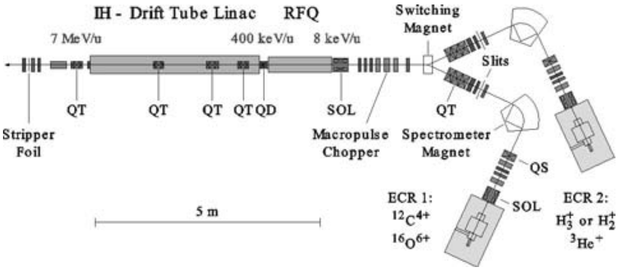

Fig. 6 Layout of the HICAT Injector Linac.

Recent DYNAMION simulations are carried out in parallel with the commissioning. The results for the LEBT simulations showed good coincidence with the MIRKO [14] calculations done during design stage.

A normalized acceptance $\boldsymbol{V_k}$ for each RFQ cell can be calculated from the solution of the Floquet equation as

$$V_k = \nu_f \frac{a^2}{\lambda}$$

where $\boldsymbol{\nu_f}$ is the minimum of the phase advance $\boldsymbol{\mu}$ on the focusing period, $\boldsymbol{a}$ - aperture of the cell, $\boldsymbol{\lambda}$ - wave length of the operating frequency [15]. The local acceptance along the HICAT-RFQ for C^{4+} beam is shown in Fig. 7. The minimum value corresponds to 327 mm*mrad (total, unnormalized) at the RFQ input energy.

Alternatively, an RFQ acceptance can be obtained from the beam dynamics simulations using wide four-dimensional grid in the transverse phase space as an input particle distribution. The particles, accelerated to the final RFQ energy, are selected from the input distribution and represent the acceptance at the RFQ entrance. This method was implemented to the HICAT-RFQ and the acceptance of 333 mm*mrad was obtained. The measured beam emittance is about 300 mm*mrad (90%).

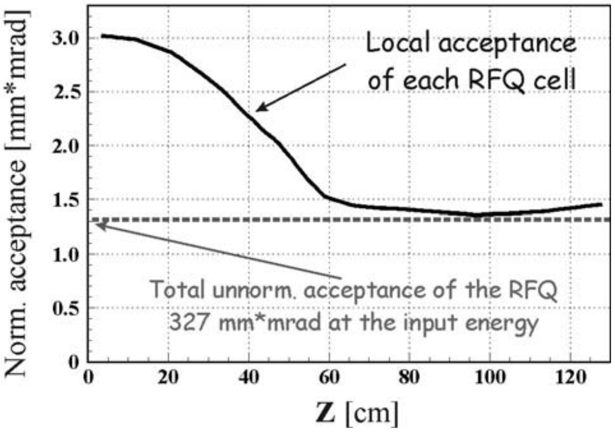

Fig. 7 Local acceptance along the HICAT RFQ.

Additional investigation of the beam dynamics in the RFQ was done assuming a special model for the transverse misalignment of the rods, potentially leading to a different output RFQ energy. The calculated results were compared with the measured energy dependence of the RFQ voltage. With this model a misalignment of the electrodes of about 250 mkm was estimated.

The final beam focusing to the HICAT-RFQ is made by a solenoid. During commissioning of the LEBT (before the RFQ was installed) several measurements of the beam emittance had been done (50 cm behind the solenoid). The distance from the solenoid to the RFQ entrance is only about 10 cm. The magnetic field of the solenoid was varied in the range from 40% to 60% of the nominal value to provide for a reasonable beam size at the position of emittance measurement device. The obtained data were used to generate macroparticle distributions which were simulated backward through the solenoid and again forward, but with the design value of the solenoidal B-field. The calculated macroparticle distribution in the horizontal phase space at the RFQ entrance is shown in Fig. 8 (vertical one is very similar). The ellipse represents the acceptance. As shown, a significant number of the particles is outside of the acceptance due to the emittance deformation. This fact was confirmed by beam dynamics simulations for the RFQ when a particle transmission of about 50% was calculated. An optimization of the matching is recently under investigation.

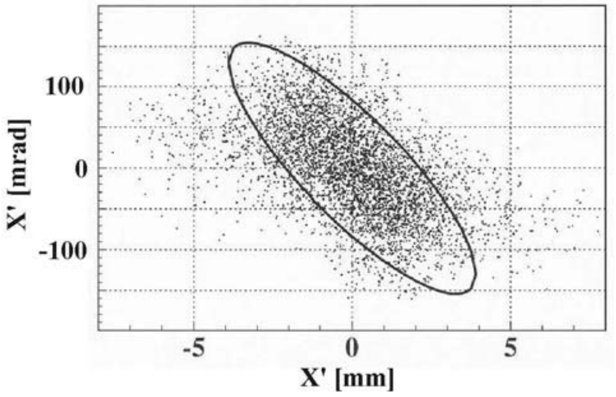

Fig. 8 Particle distribution (X-X' plane) at the HICAT-RFQ entrance. The ellipse represents the RFQ acceptance.

CONCLUSION AND OUTLOOK

End-to-end simulation studies could potentially be used to investigate and optimize the overall machine performance as well as the expected impact of different upgrade measures. The reliability of the results simulated with the multiparticle code DYNAMION was demonstrated for several linacs in the leading accelerator centers (ITEP, GSI, CERN, ANL and others). Recently the DYNAMION is successfully implemented for the design, commissioning and optimization of the major GSI linac projects: UNILAC-upgrade for FAIR, FAIR-proton linac and HICAT facility for the cancer therapy in Heidelberg.

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