ADVANCED BEAM MATCHING TO A HIGH CURRENT RFQ

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Abstract

The High Current Injector (HSI) of the heavy ion linac UNILAC at GSI comprises the transport lines, the RFQ and two DTL tanks. Beam matching to the RFQ acceptance with a magnetic quadrupole quartet has been worked out manually during commissioning and operation of the machine. Due to a strong overlapping of the field from neighbouring quadrupole lenses, a standard optics calculation does not provide for the required reliability. Advanced beam dynamics simulations have been done with the macroparticle code DYNAMION. The superposition of the measured magnetic fields of each quadrupole was taken into account. The quadrupole settings were optimized using the Monte-Carlo method. Two solutions have been found in accordance with the general theory of particle optics. Beam dynamics simulations with new quadrupole settings show an increased particle transmission through the RFQ. The results of numerical study have been confirmed during experimental campaigns. An improved performance of the whole HSI has been demonstrated. The proposed algorithm and a comparison of the measured data with result of simulations are presented.

INTRODUCTION

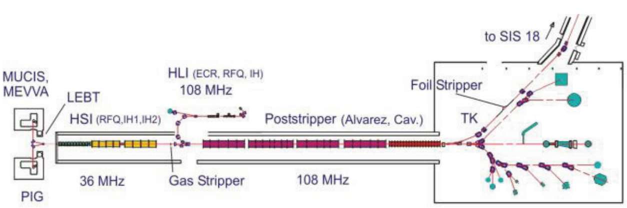

Fig. 1: Schematic overview of the GSI UNILAC and experimental area.

Besides two ion source terminals and a low energy beam transport system (LEBT) the High Current Injector of the GSI UNILAC (Fig. 1) comprises a 36 MHz RFQ accelerating the ion beam from 2.2 keV/u up to 120 keV/u and a short RFQ adapter (Superlens). The IH-DTL, consisting of two separate tanks, accelerates the beam up to the energy of 1.4 MeV/u. After stripping and charge state separation the Alvarez DTL provides for beam acceleration up to 11.4 MeV/u. The transfer line (TK) to the synchrotron SIS 18 is equipped with a foil stripper and charge state separator system. Several upgrade measures have been realized for UNILAC since the last years. Nevertheless, the beam intensity and brilliance are still a factor of five below FAIR requirements [1]. Besides hardware upgrade, further improvement of the UNILAC performance strongly requires for an optimum beam matching to each accelerating-focusing section.

HIGH CURRENT HSI-RFQ ACCEPTANCE

Assuming low beam current and smooth approximation, a local normalized acceptance V_k for each RFQ cell can be calculated from the Floquet functions, which are the solution of the Mathieu-Hill equation for particle motion:

$V_k = \nu_f \dfrac{a^2}{\lambda}$, $\nu_f = \dfrac{1}{\rho^2}$, where ρ is a module of the Floquet function, a - aperture of the cell, λ - wave length of the operating frequency; ν_f can be treated as a minimum of the phase advance μ on the focusing period.

The low current HSI-RFQ acceptance (Fig. 2) has been also evaluated from results of dedicated beam dynamics simulations. The acceptance area (approx. 400 mm*mrad) and orientation correspond well to the calculated minimum of the local acceptance along the channel.

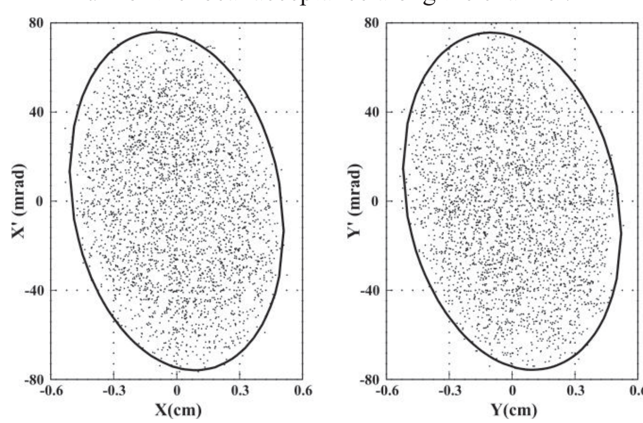

Figure 2. Low current HSI-RFQ acceptance

In case of significant beam current, the values of μ and ν_f decrease (tune depression). Quantitavely it can be calculated using the Coulomb parameter, which combines parameters of the beam and accelerating channel [2].

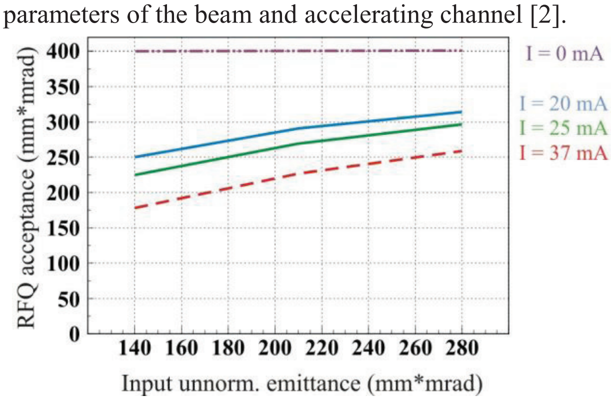

Fig. 3: "High current" acceptance of the HSI-RFQ (unnormalized) as a function of the input beam current and emittance.

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Recent measurements directly behind GSI UNILAC ion source terminal demonstrated an U^{4+} beam current up to 37 mA [3]. Fig. 3 represents the calculated high current acceptance of the HSI-RFQ in dependence of the input beam current and emittance. Also matched Twiss parameters for each value of input beam brilliance could be calculated in accordance with the theory.

BEAM MATCHING TO THE HSI-RFQ

Beam matching to the HSI-RFQ acceptance is performed by four magnetic quadrupoles (Quadrupole Quartet, QQ). Due to the short distance between lenses and relatively high aperture, an overlapping of the magnetic field from neighbouring quadrupoles makes a serious influence on beam dynamics. Additionally, strong magnetic field being applied to particles with high amplitude, provide for significant non-linear deformation of a 6D beam phase space [4].

Absence of beam diagnostics between QQ and RFQ allows the optimization procedure only for the whole system QQ+RFQ. Recently used set of QQ gradients was found experimentally. Obviously it is a compromise between beam matching to the RFQ acceptance and particle losses inside the QQ.

The standard envelope codes for beam line optimization (with quadrupoles described separately and as "squared") don't take into account an overlapping of magnetic field from the neighbouring quadrupoles. Also the use of paraxial approximation leads to simplified calculations of 3D particle motion in magnetic field. Therefore such codes can provide only for roughly estimated settings for the HSI QQ.

Also only one solution for the matched line settings is usually obtained by use of a standard envelope software, while general theory predicts four solutions for a common case of four variable elements. As technically a polarity of the quadrupoles is fixed, such four focusing-defocusing elements might provide up to two independent solutions.

USE OF MULTIPARTICLE DYNAMION CODE FOR AN OPTIMIZATION

Versatile multiparticle code DYNAMION [5] is foreseen for an advanced and reliable beam dynamics simulations for different types of accelerating-focusing channels. Besides a standard input particle distribution as KV, truncated Gaussian, waterbag etc., generated inside the code, an external 6D set of particle coordinates and velocities could be used as an input data.

Electrical and magnetic field for standard linac elements are typically calculated inside DYNAMION, but also could be introduced as a 3D mapping, obtained from an external software or direct field measurements. In particular a magnetic field for the chain of quadrupoles could be calculated (inside the code) as a superposition of the field distributions, measured for each quadrupole separately. Obviously, a shape of field overlapping changes in accordance with settings for each quadrupole.

Generally DYNAMION code is not foreseen for a typical beam line optimization. Nevertheless it was slightly modified to solve such specific problem: numerous multiparticle beam dynamics simulations (in automatic mode) with random settings for four quadrupole lenses, each time taking into account recalculated overlapping of measured field.

MEASURED DATA

The horizontal and vertical beam emittances (Fig. 4, top) have been measured with slit-grid device in front of the QQ for low beam current of about 100 mkA. Related particle distribution (Fig.4, bottom) has been generated with the particle density proportional to measured intensity inside each bin (0.5 mm x 1.7 mrad). Ellipses contain 90% of particles for each phase plane separately.

A coupling of the horizontal and vertical phase planes has been done randomly, but taking into account elliptical shape of the beam in space of real coordinates and real velocities (angles).

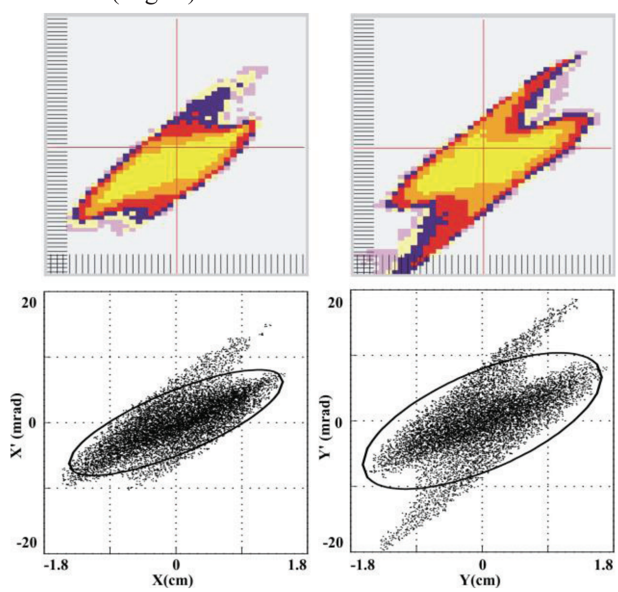

Figure 4. The measured horizontal and vertical beam emittances (top); generated macroparticles (bottom)

A magnetic field for each lens of the HSI quadrupole quartet has been precisely measured with the 3D Hall probe. A field distribution, as well as a field gradient along beam axis have been stored in the separate files.

MATCHED SOLUTIONS

Based on experimental experience and previous simulation results, a full neutralization of space charge along the LEBT was assumed. On this reason, only for an optimization procedure (tens thousands of runs) a simplified set of macroparticles could be used to reduce simulations CPU time to some hours. Thus 100 particles have been generated, with coordinates for both planes uniformly distributed along the 90%-ellipses (Fig. 4).

Dedicated set of beam dynamics simulations was performed with Monte-Carlo method, randomly varying four QQ gradients in the full range (0 - 12 T/m). A distribution of the magnetic field gradient along the beam line (including field overlapping) has been automatically recalculated each run in accordance with QQ settings.

Every run of beam dynamics simulations with a random set of quadrupole gradients provides for a particle distribution at the RFQ entrance. A mismatch parameter for each particle ensemble was calculated for both transverse planes together as an rms deviation from the input 90%-ellipses (Fig. 4), transformed to the Twiss parameters for low current HSI-RFQ acceptance. The only QQ settings which lead to a low mismatch parameter have been stored and afterwards analysed. Additional filtering was applied during the simulations to exclude those combinations of quadrupole gradients, which lead to even one from 100 "ideal" particle lost inside lenses.

As expected, two different QQ settings, leading to a low mismatch factor, have been found (Fig. 5). One solution represents well the "old" gradients for quadrupoles QQ_1-QQ_4 (2-4-6-8 T/m), which have been found experimentally during new HSI RFQ commissioning in 2009. While "new" solution proposes about 8 T/m for all four QQ gradients.

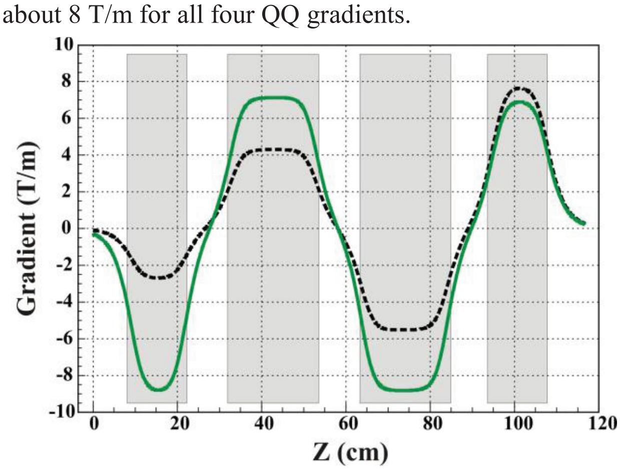

Figure 5. "Old" (dashed) and "new" (solid) magnetic field gradient along quadrupole quartet.

Similar matching optimization for intense beams with relatively bigger emittances follow this trend, but typically with higher quadrupole gradients for "old" solution (1-3-6-12 T/m) and lower ones for the "new" settings (5-6-6-5 T/m).

HSI-RFQ SIMULATIONS

The found QQ settings (Fig. 5) have been introduced into two independent DYNAMION simulations using the input particle distribution generated from measured emittance (Fig. 4). A realistic description of the HSI-RFQ external field [2] has been implemented. The space charge effects were neglected for this case due to the measured Ar^{1+} beam current of about 100 mkA.

The results of beam dynamics simulations with new quadrupole settings demonstrated significantly higher particle transmission through the system QQ+RFQ: 96% instead of 85% with old settings. Also beam brilliance behind HSI-RFQ strongly increased due to the higher beam current, as well as lower beam emittance in transverse (Fig. 6) and longitudinal phase space.

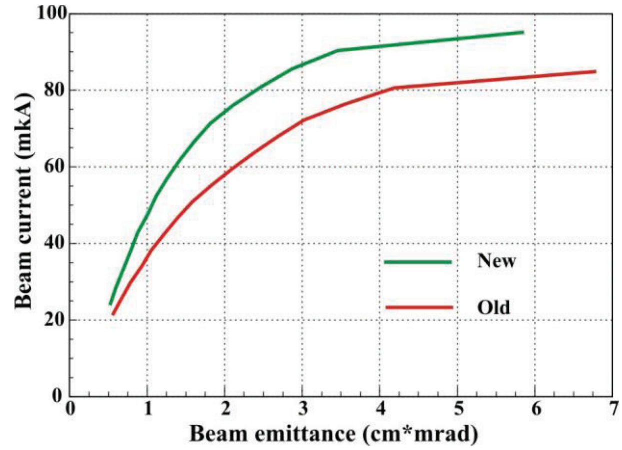

Figure 6. Beam intensity inside a given beam emittance behind HSI-RFQ with old (red) and new (green) setting for Quadrupole Quartet.

EXPERIMENTAL RESULTS

During last years several beam experiments for HSI optimization have been performed. The results of the numerical investigations for new QQ settings have been confirmed with different ions and beam intensities. For the low current argon beam a 100% transmission for the whole HSI (LEBT, RFQ, MEBT, two IH-DTL tanks) has been reached first time since commissioning in 1999, while previously achieved particle transmission didn't exceed 85%. An increased HSI transmission of about 10% was demonstrated also for some high current beams and LEBT settings, even with significantly higher beam emittances at QQ entrance. An additional fine tuning for the LEBT, as well as an optimization of the linac sections behind RFQ are recently under numerical investigation.

Also experiments in 2014 with tantalum beam (about 4 mA at QQ entrance) demonstrated serious improvement of the front-end particle transmission from 48% to 71%. Evaluation of the measured data and corresponding beam dynamics simulations are in progress.

CONCLUSION

- two different setting for the Quadrupole Quartet, providing for optimum front-end transmission, have been found during dedicated beam dynamics study;
- one of the solutions corresponds well to the settings which already have been found experimentally in 2009;
- new solution leads to a significant improvement of the front-end performance
- new QQ settings typically provide for significantly higher beam currents, as well as for lower beam emittances behind HSI-RFQ
- an improved performance of the whole prestripper section of UNILAC (up to beam energy of 1.4 MeV/u) was demonstrated experimentally for different ions and beam intensities.

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