AN ION BEAM MATCHING TO A LINAC ACCELERATING-FOCUSING CHANNEL

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Abstract

A modern linear accelerator of ions is a long chain of different accelerating-focusing structures. The design of new linacs, as well as an upgrade and optimization of operating facilities, requires precise and reliable beam matching with the subsequent sections. Proper matching of the beam to the channel allows to improve the performance of the whole linac and to reduce the specific costs. Additionally it helps to avoid particle loss in high energy high intensity linacs and to reduce activation. Generally a matching algorithm combines precisely measured or calculated accelerating-focusing external fields and experimentally obtained details of the beam parameters (energy, current, and emittance) with an advanced code for beam dynamics simulations including space charge effects. Measurements and experimental results are introduced into a code as input data. The described algorithm has already been successfully implemented for several GSI projects: upgrade of the GSI heavy ion linac UNILAC, ion linac for the cancer therapy, proton linac for the FAIR facility, GSI linac for deceleration of the heavy ions (HITRAP), facility for laser acceleration of ions (LIGHT) and others. Measured data and results of beam dynamics simulations leading to an achieved improvement of the linac performance are presented.

INTRODUCTION

Several linac projects are recently under consideration at the Helmholtzzentrum GSI (Darmstadt) in collaboration with other leading accelerator centers.

The Facility for Ion and Antiproton Research at Darmstadt (FAIR) requires a serious upgrade of the GSI high current heavy ion linac UNILAC [1]. During the last decade a significant improvement of the UNILAC was successfully performed. Several hardware upgrades, also resulting in an improved beam matching with the downstream structures, are recently carried out for further increase of the beam- intensity and -brilliance [2].

A dedicated proton linac (up to 35 mA at 70 MeV) is foreseen to serve for the FAIR scientific antiproton program [3]. Tolerances for the beam matching to the p-RFQ were studied using realistic particle distributions coming from the ion source.

An accelerator dedicated for the cancer treatment at Heidelberg (HIT) is in routine operation since 3 years [4]. A significant improvement of the low energy beam matching to the RFQ with minor modification of the RFQ electrodes was proposed and already realized at similar German facilities at Marburg and Kiel.

GSI heavy ion decelerator HITRAP is still under commissioning stage [5]. A longitudinal matching to the decelerating RFQ was investigated.

In frame of the LIGHT collaboration (Laser Ion Generation, Handling and Transport) a test setup, based on the GSI Petawatt laser PHELIX, is integrated into one of experimental UNILAC beam lines [6]. A 6D matching of the laser generated proton beam to a conventional accelerating structure is one of the main project goals.

During the last years a set of beam dynamics simulations for the different GSI projects were done using the versatile multiparticle code DYNAMION [7]. A general feature of the code is a solving of the full 3D-equation of particle motion. Therefore non-linear effects, as well as high order chromatic aberrations, are automatically included into the simulations. External electromagnetic fields are calculated with high reliability inside the code or can be used as an externally modeled or measured 3D field mapping. Space charge effects might be calculated in the code using different solvers including particle-particle interaction, PIC solver or semi-analytical algorithm [8, 9].

UNILAC UPGRADE AND OPTIMIZATION

Besides two ion source terminals and a low energy beam transport system (LEBT) the High Current Injector (HSI) comprises a 36 MHz IH-RFQ accelerating the ion beam from 2.2 keV/u up to 120 keV/u. The IH-DTL accelerates the beam up to 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 foil stripper and another charge state separator system.

New Design of the HSI-RFQ

In 2009 a newly designed HSI-RFQ accelerating-focusing channel was successfully commissioned [10]. It provides for the higher acceptance, as well as for the improved beam matching to the RFQ, taking into account typical beam emittances measured in the LEBT (Fig. 1). For the beam dynamics simulations during the design stage the 2D particle distributions were generated from the measured transverse beam emittances. The number of particles is proportional to the measured intensity of each bin. The 4D transverse distribution of particles was randomly combined from both 2D horizontal and vertical data assuming an elliptical shape of the beam in real space. Longitudinal position and velocity of particles was defined assuming continuous beam.

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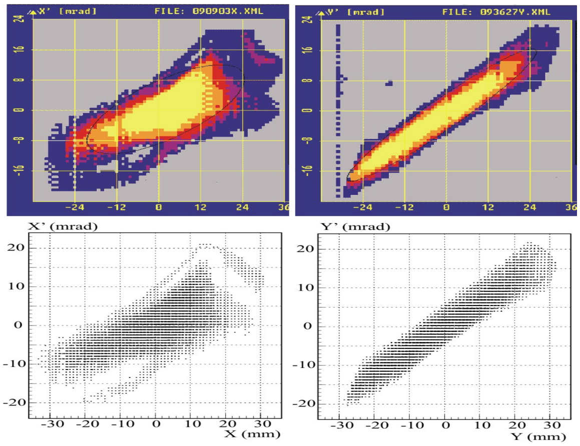

Figure 1: Measured horizontal and vertical beam emittances (top) and related particle distribution (bottom) generated for beam dynamics simulations.

"High Current" RFQ Acceptance

Assuming smooth approximation [11], a local normalized acceptance V_k and phase advance μ for each RFQ cell can be calculated from the Floquet functions (solution of the Mathieu-Hill equation for the particle motion). In case of a significant beam current, the values of μ and V_k decrease (tune depression). Quantitatively it can be calculated using the Coulomb parameter h, which combines parameters of the beam and the channel:

$h = j \cdot \dfrac{B\lambda}{\mu_0 \beta I_0}$, where $j = \dfrac{I}{V_p}$ - beam brilliance, I - beam current, V_p - beam emittance, B - ratio of the peak current to the pulse current, λ - wave length of the operating frequency, I_0=3.13·10^7·A/Z - characteristic current, A, Z - mass and charge numbers, μ_0 - phase advance for low beam current, β - relative velocity of particle. The phase advance and the acceptance of the channel can be evaluated as $\mu = \mu_0\left(\sqrt{1+h^2} - h\right)$, $V_k = V_{k0}\left(\sqrt{1+h^2} - h\right)$.

The Coulomb parameter reaches its maximum value along RFQ channel in the gentlebuncher. The related minimum of the local acceptance along the RFQ channel is 0.856 mm*mrad for an U^{4+} beam [12]. It corresponds to the total unnormalized acceptance at the RFQ entrance (2.2 keV/u) of about 400 mm*mrad. On the base of the previous experimental investigations an area of interest was defined: U^{4+} beam current up to 37 mA; beam emittance at RFQ entrance up to 400 mm*mrad.

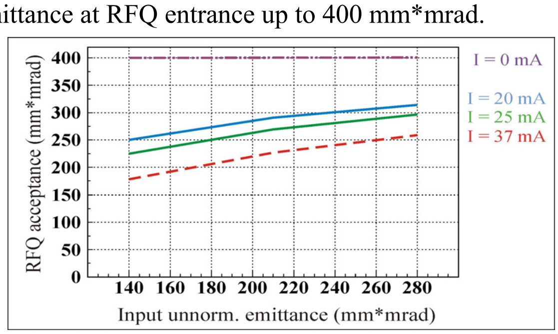

Figure 2: "High current" acceptance of the RFQ as a function of the input beam current and emittance.

Figure 2 represents an acceptance of the new HSI-RFQ in dependence of the input beam current and emittance. Beam current of about 25 mA at the RFQ entrance is required for the FAIR. In this case acceptance of the RFQ is limited to 300 mm*mrad. An increase of the beam brilliance leads to a decrease of the RFQ acceptance. Therefore further design of the new compact injection line [13] should take into account a beam matching to a "high current" RFQ acceptance, which strongly depends on the beam brilliance.

GSI PROTON LINAC

A proton beam coming from the ion source is transported and matched to the p-RFQ using two solenoids. Complicate simulations of the beam formation and transport were done in frame of the GSI-CEA collaboration [14]. A calculated particle distribution with non-uniform shape at the RFQ entrance was artificially transformed varying the beam- spot and -divergence. Particle transmission for the RFQ was calculated taking space charge effects into account. Suitable matching in a wide range of Twiss parameters was demonstrated.

HIT INJECTOR LINAC

The HIT injector was commissioned in 2006.Particle transmission for the front-end system, namely matching solenoid and the RFQ, was only about half of the design values. The problem to increase the performance of the front-end system was investigated.

For the simulations data of the beam emittance measurements behind the solenoid in horizontal (X-X') and vertical (Y-Y') planes were used. During measurements the magnetic field of the solenoid was set to app. 50% of the nominal value. This allowed for an emittance measurements with the slit-grid device. Direct measurements with design settings of the solenoid are not possible due to an extremely strong focusing of the beam to the RFQ entrance. 2D particle distributions were reconstructed from the measured data in accordance with intensity in each bin. The particle coordinates in X-X' and Y-Y' phase planes were randomly combined to a 4D distribution assuming round shape of the beam in real planes X-Y and X'-Y'. Longitudinal phase coordinates of the particles were generated assuming continuous beam.

The solenoid was described in DYNAMION code as a 3D magnetic field mapping, created from the dedicated measurements at GSI. Generated particle distribution was transformed backwards through the solenoid with 50% of nominal field, as during experiment. Afterwards a particle motion was simulated forward through the solenoid, but with a magnetic field close to the design settings. A general approach was an optimization of the beam matching to the RFQ acceptance.

The comparison of the measured and calculated backward-forward emittances has been done. The results of some simulations gave calculated beam emittances significantly higher than measured ones. The main reason of this discrepancy is the reconstruction of the 4D transverse distribution from measured 2D data without taking into account a strong coupling between transverse phase planes due to the solenoidal type of focusing. To avoid this problem an advanced algorithm for a generation of the particle distribution was proposed and successfully implemented.

An artificial Gaussian particle distribution with design Twiss-parameters and doubled emittances (to cover a wide range of the 4D phase coordinates) was created in front of the solenoid. This distribution was transformed forward through the solenoid (with 50% of nominal field, as during experiment). As a result the "simulated" particle distribution at position of emittance measurements was obtained. Obviously the simulated for each particle 4D transverse coordinates $P_s(x,x',y,y')$ automatically include a coupling between horizontal and vertical phase planes.

For each "measured" particle with coordinates x_m, x'_m in X-X' plane one can find the closest particle from the "simulated" distribution with coordinates x_s, x'_s. Relative distance in X-X' plane is the minimum of the value

$$\Delta = \sqrt{\left((x_m - x_s)/x_{\max}\right)^2 + \left((x'_m - x'_s)/x'_{\max}\right)^2},$$

where x_{max}, x'_{max}, y_{max}, y'_{max} are the maximums of the corresponding phase coordinates.

For the found "simulated" particle with horizontal coordinates x_s, x'_s its vertical coordinates y_s, y'_s are known from the results of simulations. Therefore the particle, closest to the y_s, y'_s, can be selected from the vertical "measured" distribution calculating minimum of the value

$$\Delta = \sqrt{\left((y_m - y_s)/y_{\max}\right)^2 + \left((y'_m - y'_s)/y'_{\max}\right)^2}$$

Implementing this procedure for each "measured" particle (Fig. 3) a 4D distribution with reliable coupling between horizontal and vertical phase planes was combined and used for a beam matching and the HIT-RFQ redesign.

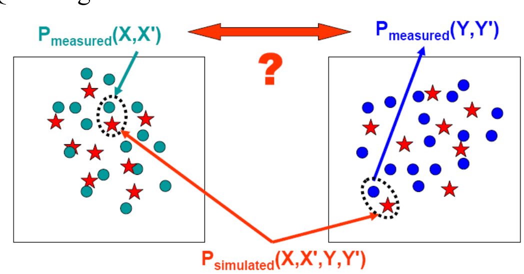

Figure 3: A coupling of the 2D particle distributions, generated from emittance measurements, to a 4D one.

HITRAP DECELERATOR

Highly charged ions up to U^{92+} provided by the GSI accelerator facility will be decelerated and subsequently injected into a Penning trap for further cooling almost to rest. A longitudinal matching of the beam, coming from the decelerating DTL [15], to the decelerating RFQ [16] was analyzed. The DYNAMION beam dynamics simulations were carried out using measured 3D-surface of the fabricated RFQ electrodes. On the base of the simulation results a complete redesign of the HITRAP-RFQ was recommended.

LIGHT COLLABORATION

The general goal of the LIGHT project is a study of the transport, collimation and rotation of the laser generated ion beam and its final matching to a conventional accelerator. An integration of the LIGHT test stand to the UNILAC beam line provides for an unique experimental possibility to prove a beam line setup and to calibrate in advance the beam diagnostic devices using standard UNILAC beam with well known parameters. The results of DYNAMION investigation for the laser accelerated 10 MeV protons are used for test stand the layout. Important project task is a beam matching to a conventional linac.

CONCLUSION

The versatile DYNAMION code is a powerful tool for linac design, optimization and advanced beam matching using particle distributions generated from measurements.

Several upgrade measures, continuous numerical and experimental optimization together with further beam diagnostics development led to a significantly improved performance of the whole UNILAC. An Ar^{18+} beam current of 8 mA with final UNILAC energy of 11.4 MeV, reached in 2010 at SIS18 entrance, is a world record for the heavy ion high current machines.

A set of beam dynamics simulations for GSI proton linac demonstrated proper and reliable matching of a non-uniform realistic particle distribution from LEBT to the p-RFQ acceptance.

Minor modification of the HIT-RFQ electrodes leads to an improved beam matching and potentially up to 50% higher linac transmission. The new shape was already realised for the operating facilities at Marburg and Kiel.

A reliable investigation of the longitudinal beam matching to the HITRAP-RFQ confirmed and explained an experimental result.

An unique experimental test stand was built at GSI in frame of the LIGHT project. A transport of the laser accelerated beam and its matching to the conventional accelerating structures is one of the recent tasks.

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