BEAM DYNAMICS OF HICANS PLATFORM: BENCHMARKING RF-TRACK SIMULATIONS OF THE LEBT, RFQ AND TRANSFER LINE

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Abstract

We present beam dynamics studies for the future compact accelerator neutron source HiCANS platform, carried out with the RF-Track code. The simulations were used to optimize the layout and geometry of various components of the beam line. The results are compared to other codes and measurements. The studied beamline consists of the LEBT with two solenoids, an RFQ and a dogleg style transfer line. The RFQ was modeled using fine-grained field maps. The simulations were used to optimize the LEBT geometry for maximum RFQ transmission. To benchmark the LEBT simulations we studied the magnetic focusing of different hydrogen species and compared it to measurements in the existing ESS-Bilbao injector. Furthermore, the transmission in the RFQ and output phase space was simulated for different beam currents, and the results were compared against GPT. The lattice of the transfer line was designed and error studies were performed using RF-Track and validated with TraceWin. We demonstrate how RF-Track serves as fast and convenient tool for extensive optimization processes including full particle tracking and calculation of space charge effects.

INTRODUCTION

HiCANS platform is a high-current accelerator-driven neutron source, currently under development at ESS-Bilbao, Spain [1]. Its ion source provides protons at 45 keV in 1.5 ms-pulses with a frequency of 30 Hz and peak current of 50 mA. A LEBT equipped with two solenoids matches the beam to the next stage, the RFQ (352.21 MHz), which accelerates the beam up to 3 MeV [2, 3]. A dogleg-style transfer line guides the beam to the target and moderator unit, equipped with a lithium spallation neutron source [4]. HiCANS platform is a fully fledged neutron source, but it also serves as demonstrator for a future expansion with a drift-tube LINAC, called Argitu.

Beam dynamics simulations helped to improve the LEBT design, study the RFQ and define the layout of the transfer line. As principal tool the RF-Track code was used [5]. It allows multi-particle tracking in time in a 3D volume with full space charge calculation. An advantage of RF-Track is that the space charge calculation can be performed at a larger step size than the integration, which speeds up the simulation. The space charge effects are calculated by the particle-in-cell method. We integrated RF-Track into a custom Python framework that allows us to quickly create and run modular simulations, which also can be accessed by function calls in optimization processes. A demonstration of this implementation can be found in reference [6].

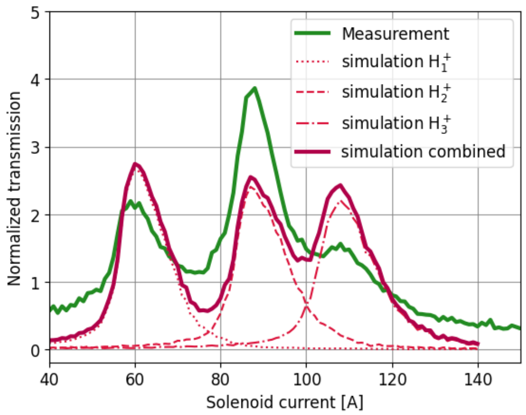

Figure 1: Scan of solenoid focusing: the measured and simulated transmission of different hydrogen species.

SIMULATION VALIDATION

We validate the accuracy of the simulations with measurements and by comparing RF-Track results with other codes. The RF-Track settings itself are optimized by producing a slow, but highly accurate reference simulation, using the 4th-order Runge Kutta method, and then we try to reproduce the results using faster algorithms and larger time steps until convergence is achieved.

Experimentally, we study the magnetic focusing of the hydrogen-species H^+, $H_2{}^+$ and $H_3{}^+$ in the LEBT by measuring the beam current while scanning over the solenoid current. The simulated and measured transmission are shown in figure 1. The peak positions are in good agreement within a few Ampere.

We also compared beam dynamics simulations of the RFQ between RF-Track and GPT 2.8 [7]. The output phase space distributions between both codes show small differences, however, RF-Track provides a more accurate interpolation of the field map next to wall boundaries (note that we used a very old version of GPT).

Finally, we simulated the beam trajectories in the transfer line with RF-Track and TraceWin [8]. The comparison of the beam envelopes is shown in figure 2. On the first meters, the envelopes are in very good agreement. Towards the end of the transfer line, deviations appear, which can be explained by different quadrupole and sector bending magnet models used in each simulation.

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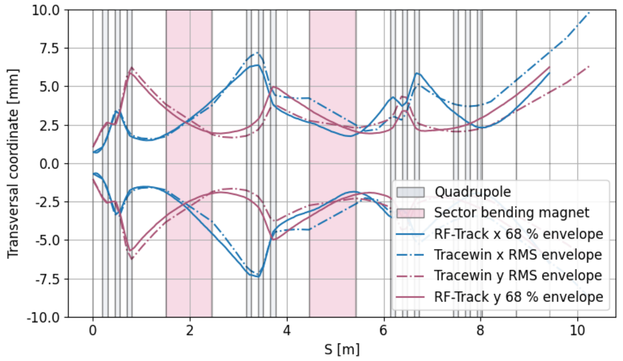

Figure 2: Beam envelopes in the transfer line, comparison of results from RF-Track and TraceWin.

BEAM DYNAMICS RESULTS

LEBT and RFQ

Guided by simulations, an upgrade of the existing ESS-Bilbao injector was designed. We focused on reducing the overall length and increasing the aperture in order to maximize the transmission and match the RFQ acceptance phase space. In the LEBT, tracking of a 100 ns bunch is performed with the analytic algorithm on a 0.5 ns time step. The bunch is generated at the output of the the extraction column with an energy of 45 keV. For the Courant-Snyder parameters, we assume an initial normalized RMS-emittance of 0.25 mm mrad, $\alpha_{x,y} = -2$ and $\beta_{x,y} = 0.1$. However, a bottle neck aperture between the extraction column and the first solenoid ultimately defines the beam geometry in the LEBT. To emulate the space charge compensation effect, the reference current of 30 mA is scaled down by a factor of 10. The space charge kicks are applied every 5 ns and act only on the transversal coordinate (since the simulated bunch is contained within a larger pulse), achieved by using only one particle-in-cell mesh point in the z-direction. See also reference [9] for previous simulation studies of the LEBT.

As input for the RFQ the simulated output of the LEBT is used. The bunch is cut down to 15 ns, which at the RFQ frequency of 352.21 MHz is split into 5 bunches. In the analysis we take only the central bunch into account, thus correctly accounting for longitudinal space charge effects. The integration time step is 0.025 ns, using the analytic algorithm, and every 5 steps a space charge kick is applied. The RFQ is included as 3D-field map with a transversal resolution of 0.1 mm and 0.5 mm longitudinally. It is based on the actual manufactured model including the measured gaps between the three segments. The transmission through the RFQ, normalized to the number of particles at the RFQ entrance, ranges from 97.8 % at 0 current to 93.8 % at 60 mA beam current (the maximum current for prospective future uses). The simulated output of the RFQ predicts a mean energy and standard deviation of 2.99(3) MeV, and a bunch 1σ-width of 62 ps. The transversal Courant-Snyder parameters (RMS) are $\epsilon_{\text{norm}} = 0.3$ mm mrad, $\alpha_x = 0.14$, $\alpha_y = -0.40$, $\beta_x = 0.13$ mm, and $\beta_y = 0.11$ mm.

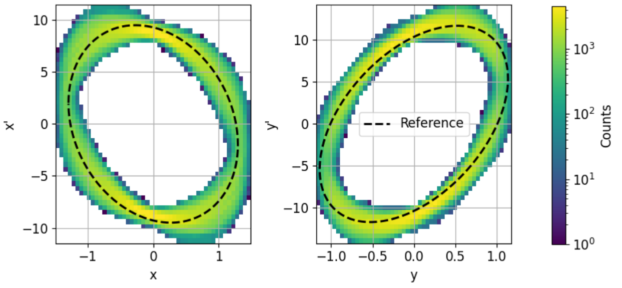

Figure 3: The RFQ output phase space ellipsis of 500 simulation runs with voltage errors.

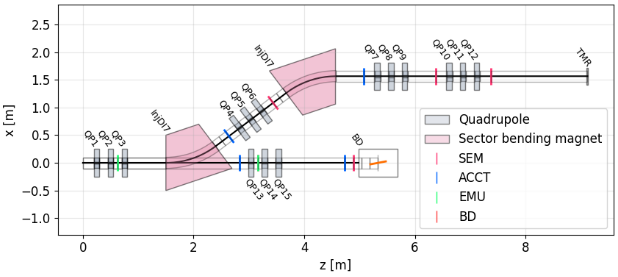

Figure 4: The transfer line lattice. The end of the RFQ is located at $z = 0$.

In operation, thermal expansion and tuning errors can cause position-dependent deviations of the inter-vane voltage from the reference value of 85 kV. To study these errors, we apply a modulation with a single minimum to the field map. The RFQ continues to show good performance for voltage drops smaller than 10 %. The worst case is a drop just in the middle of the RFQ. In this case, a drop of 10 % reduces the transmission to 83 %. We perform simulations while scanning over the drop position and amplitude up to 10 % to determine errors of the output beam parameters. In figure 3 we show the phase space ellipses for 500 runs with these RFQ voltage errors.

Transfer Line

We designed a transfer line to transport the beam from the RFQ output to the target station over 9 m longitudinally and 1.5 m transversely. The basic lattice was defined using TraceWin. The dogleg-style transfer line features two 38.25° sector bending magnets and 12 quadrupole magnets arranged in triplets. 2D-steerers are integrated into each quadrupole. At the first bending magnet, a beam dump line is added with additional 3 quadrupoles. The beam line is equipped with several AC current transformers (ACCTs), secondary emission monitors (SEMs) and an emittance meter unit (EMU). A drawing of the lattice is shown in figure 4.

We study the beam dynamics with RF-Track, using the Runge-Kutta (2, 3) method with a step size of 0.15 ns. The space charge step size is set to 3 ns. The input beam is the simulated output of the RFQ. The quadrupoles are implemented as analytical fields, while the bending magnets are included as field maps. The quadrupole magnets follow a design prepared for the ESS MEBT [10]. These magnets allow a beam pipe diameter of 36.8 mm. This prohibits an

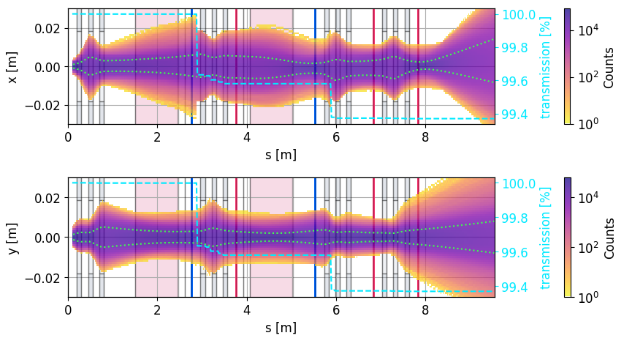

Figure 5: The combined trajectories of 50 runs with random errors. The dotted lines represent the RMS beam envelopes. See figure 4 for the element legend.

achromat configuration, as the beam size would expand beyond the aperture. By performing an optimization with the objective to maximize the transmission, we found gradients that provide a transmission ~100 % while respecting the beamline diameter, with no gradient exceeding 15 T/m. We can disregard the dispersion, since the transfer line is followed directly by the spallation source. After error studies confirmed the robustness of the lattice, we performed a virtual experiment with combined errors, where we steer the beam using only emulated data from the diagnostics. For the misalignment of the magnets, we generate values on a linear scale in the range of ±0.25 mm for the displacement and ±2.5 mrad for the rotation, each on three axes. The input beam is generated with errors according to the RFQ voltage modulation (see figure 3). Gradient errors at realistic values were found to have a negligible effect. The resulting trajectories, combined from 50 runs with random errors, are shown in figure 5. The averaged transmission is >99 %.

OPTIMIZATION PROBLEMS

In many of the studies presented here, optimization problems had to be solved: maximizing the RFQ transmission as a function of the solenoid currents and geometry of the LEBT, and, regarding the transfer line, to find optimum quadrupole gradients and corrector strengths. In the following, we describe the optimization process for the case of the transfer line virtual experiment, where we only use emulated data from the diagnostics. This data is the normalized current $i = i_{\mathrm{ACCT}}/i_0$ from the ACCTs, where i_0 is the initial beam current, and the beam position from the SEMs, where we evaluate the beam center $r = \sqrt{\bar{x}^2 + \bar{y}^2}$, starting from histograms with 20 bins (i.e. SEM wires) for each coordinate x and y. We also define the "focus" f_{SEM}, the relative transmission within an aperture a at the SEM:

$$f_{\mathrm{SEM}} = \frac{1}{\sqrt{2}} \cdot \sqrt{\left(\frac{\sum_{|x|<a} c(x)}{\sum c(x)}\right)^2 + \left(\frac{\sum_{|y|<a} c(y)}{\sum c(y)}\right)^2},$$

where $c(x)$ and $c(y)$ are the counts on each axis. We combine these figures to define the objective function

$$f = 0.1 \cdot r - i^2 \cdot f_{\mathrm{SEM}},$$

which is to be minimized. The factor 0.1 and the square were included to speed up the convergence. For the aperture variable a we found that values between 0.5 and 0.75 times the beam pipe diameter lead to a successful optimization. When start parameters are not known, the Bayesian optimization using Gaussian Processes is effective. When a rough starting point is known, we use the COBYQA algorithm, which demonstrated to reliably find the minimum with relatively few function calls [11]. The input beam for each function call is generated from a pseudo-random scrambled low-discrepancy SOBOL-sequence, which reduces statistical noise already at low particle numbers. Locking the seed results in a smooth objective function and thus provides more accurate results and faster convergence. We optimize each quadrupole triplet sequentially to reduce the number of free parameters from 36 to 9 at a time (3 gradients and 6 steerer strengths). With 5000 particles, each function call takes ~2 s on 8 cores and the optimization of the entire beam line is completed within a few minutes.

CONCLUSIONS

We presented beam dynamics simulations prepared with RF-Track for the HiCANS platform beamline. The simulations of the LEBT were validated with measurements, and comparisons with other codes showed consistent results for the trajectories in the RFQ and transfer line. In summary, we found that RF-Track is a reliable code to study the beam dynamics in our entire beam line, and its Python integration offers a convenient interface for custom frameworks and optimization processes. With the help of the simulations we prepared an improved design of the LEBT at ESS-Bilbao, studied the beam dynamics of the RFQ and designed a lattice for the transfer line that will deliver protons to a spallation neutron source. Error studies were performed and proved the robustness of the design.

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