ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-TUPORI03

MODEL COUPLED ACCELERATOR TUNING WITH AN ENVELOPE CODE*

O. Shelbaya†, R. Baartman, O. Kester, S. Kiy, S.D. Rädel, TRIUMF, V6T 2A3 Vancouver, Canada

Abstract

Frequent linac re-tuning is needed at TRIUMF-ISAC for the delivery of rare isotope beams at a variety of mass-to-charge ratios and beam energies. This operation is of appreciable complexity due to the nature of the accelerator, consisting of a separated function, variable output energy DTL paired with an RFQ. Reference tunes, computed from a variety of beam and accelerator simulation codes, are scaled according to the beam properties, though changing beam parameters at the sources requires manual tuning of matching section quadrupoles. Using an end-to-end envelope model of the machine in the code TRANSOPTR, these tunes can now be rapidly computed, and using beam diagnostic inputs to reconstruct the beam matrix, the model can be used to dynamically re-optimize the machine tune on-line.

INTRODUCTION

Unlike multiparticle (ray-tracing) simulations, which treat beam envelopes as emergent quantities, the infinitesimal transfer matrix approach is better suited for optimization of the ion-optics settings needed to configure the machine for optimum beam quality. At TRIUMF-ISAC, the heavy-ion post-accelerator which drives nuclear science investigations, consists of an RFQ-DTL pair, which can be configured at a variable output energy, for a range of $2 \leq A/q \leq 6$, shown in Fig. 1. By its design, this machine is constantly being re-tuned to produce the various requested beam properties by the network of experiment stations it services. To date, the operational tuning methodology has called for the manual establishment of reference machine configurations, whose optics settings are in turn scaled for mass and charge. Though this is informed by beam simulations, it is a decidedly empirical tuning approach. As the demands upon the apparatus have increased, thanks to a competitive and highly subscribed experiment schedule, the overhead time associated with empirical machine tuning have become difficult to sustain.

This has motivated the development of a full model of the ISAC linac in the envelope code `TRANSOPTR`[1], which is now capable of performing start to end envelope simulations and constrained optimizations. The lightweight nature of the computation means that full machine optimizations can be done in roughly one minute, using a conventional pc. In turn this enables the writing of software which performs start-to-end optics optimizations, by locally isolating groups of 4 to 6 parameters such as quadrupoles, or any element representable by an analytic Hamiltonian. Recent beam development investigations have aimed to use a parallel envelope simulation, fed with real-time machine setpoints and using information on the beam distribution obtained from diagnostic readings. The envelope code is then used to compute optimized tunes, subject to user defined constraints upon the beam or transfer matrices, with setpoints then loaded back into the accelerator on-line. This interplay between apparatus and simulation is the premise for model coupled accelerator tuning, now under development at TRIUMF.

* Funded under a contribution agreement with NRC (National Research Council Canada).
† oshelb@triumf.ca

ENVELOPE MODEL

`TRANSOPTR` tracks a reference particle in a sliding Frenet-Serret frame, with trajectory s. Particles in this frame are located as $\mathbf{X} = (x, P_x, y, P_y, z, P_z)$. The beam distribution is represented through its covariance matrix $\boldsymbol{\sigma}$; The evolution of the rms size of the beam depends on the linear components of the forces[2]. Over a small displacement ds, $\boldsymbol{\sigma}$ transforms through the infinitesimal transfer matrix $\mathbf{M} = \mathbf{I} - \mathbf{F}ds$, and $\mathbf{I}$ is the identity. This connects to the Hamiltonian via $\mathbf{M}' = \mathbf{FM}$. The matrix $\mathbf{F}(s) = \mathbf{JH}(s)$, where $\mathbf{J}$ is the elementary symplectic matrix and $\mathbf{H}(s)$ is the Hessian matrix of the s-independent Hamiltonian. The continuous evolution of $\boldsymbol{\sigma}$ along the trajectory is given by the envelope equation:

$$\frac{d\boldsymbol{\sigma}}{ds} = \mathbf{F}(s)\boldsymbol{\sigma} + \boldsymbol{\sigma}\mathbf{F}(s)^T. \quad (1)$$

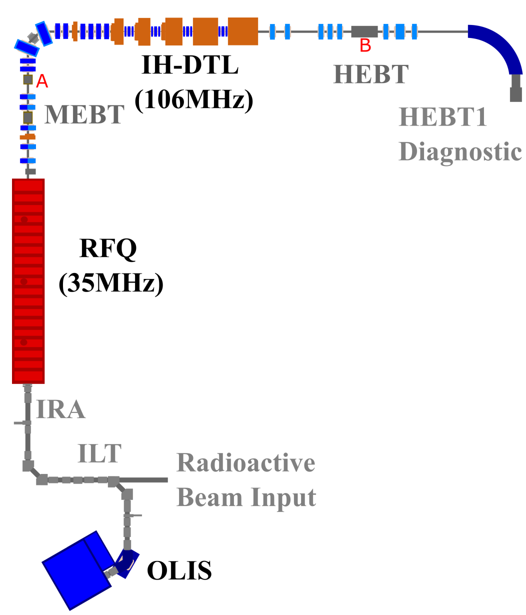

Figure 1: Overview of the ISAC-I component of the rare isotope beam (RIB) postaccelerator at the TRIUMF-ISAC facility. Stable pilot beams are provided by the OffLine Ion Source (OLIS). Movable stripping foils located at A & B.

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-TUPORI03

TRANSOPTR numerically solves both $\boldsymbol{\sigma}(s)$ and $\mathbf{M}(s)$, along with the energy and time of the reference:

$$\frac{dE_0}{ds} = \frac{\partial H_s}{\partial t} = -q\frac{\partial A_s}{\partial t}, \tag{2}$$

$$\frac{dt_0}{ds} = -\frac{\partial H_s}{\partial E} = \frac{E_0}{P_0} = \frac{1}{\beta_0 c}. \tag{3}$$

Coordinates 5 and 6 of $\mathbf{X}$ are scaled values for energy and time, an equivalent distance and momentum: $(z, P_z) = (\beta c \Delta t, \Delta E/(\beta c))$. This enables the correct treatment of accelerated beam envelopes[3, 4].

OPTIMIZATION WITH CONSTRAINTS

Figure 2 shows a 6-parameter envelope optimization in the code, which found setpoints for an Einzel lens and 5 electrostatic quadrupoles for the OLIS terminal[4] (Fig. 1). The constraints include narrow horizontal waists at the collimators defining the entrance and exit from the 60° dipole and a match to specific Twiss parameters at the simulation end, at the bottom of the figure. The optimization proceeds by minimizing the sum of the squared differences betwen the computed and desired characteristics. This method is of course not exclusive to TRANSOPTR, however its advantage stems from its structure. Written in FORTRAN, simulations are built by calling a sequence of subroutines representing the various transformations upon the $\boldsymbol{\sigma}$-matrix: drifts, dipoles, quadrupoles, but also elements defined by electric fields along s such as the Einzel lens, RFQ[3] and DTL[4] accelerators. Since each element is treated in the same framework, computations may include any available device in the code's library, producing a powerful tool for the rapid calculation, analysis and optimization of tunes on the machine.

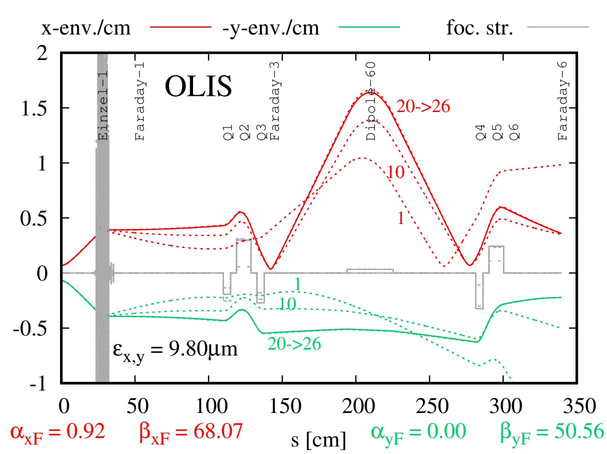

Figure 2: TRANSOPTR (x, y) 2rms envelope optimization, with labeled emittance $\epsilon_{x,y}$. Optimum Einzel lens and quadrupole set points (relative focal strengths in grey) are returned producing the match at the simulation end after 26 steps. Size constraints are imposed at the location of horizontal slits. Selected iterations are displayed and labeled by number. Fit Twiss parameters labelled at bottom of plot, Twiss-β units are [cm/rad].

AUTOGENERATION

An elements repository in the XML language is used to store the dimensions, parameters and location of the various ion-optical components along the accelerator's path. Software has been written to enable the programmatic, automatic generation of TRANSOPTR sequence files from this repository[5], enabling the user to define a starting and ending location, in addition to beam parameters and device setpoints, if desired. This changes the paradigm of modelling and analysis work, from maintaining *authoritative* versions of simulation files, to instead controlling the exactitude of the information in the XML repository. This way, file autogeneration at model execution guarantees that simulations always represent the up-to-date status of the lattice.

SEQUENTIAL TUNE OPTIMIZATION

The model can be used to compute full machine tunes from first principles, if beam parameters are available. The latter can either be obtained from reference values, or measured on-line and provided to the envelope model for interpretation, discussed in the next section. In the case of an available initial beam distribution at $s = 0$, long sequences of elements are optimized by dividing the problem into subsegments, each containing up to six elements which ensures a sufficiently high likelihood of convergence. Figure 3 shows this applied over 5 optimization steps, from the OLIS terminal up to the ISAC-RFQ. To further enable automation, the $\boldsymbol{\sigma}$- and transfer-matrix constraints are themselves stored in the XML repository, ensuring they are systematically included in each file generation.

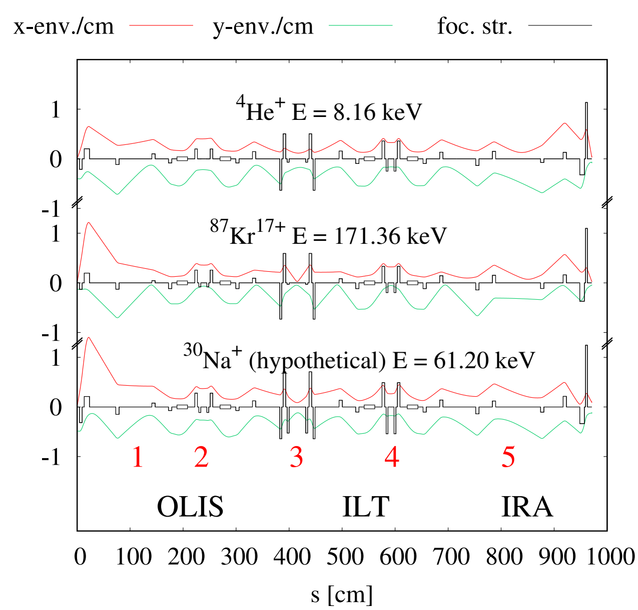

Figure 3: Sequential optimization of beamline segment from exit of OLIS dipole to ISAC-RFQ injection, for three different scenarios. In each case, beam energy is displayed. Relative focal strengths shown in black, optimization steps labeled in red.

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-TUPORI03

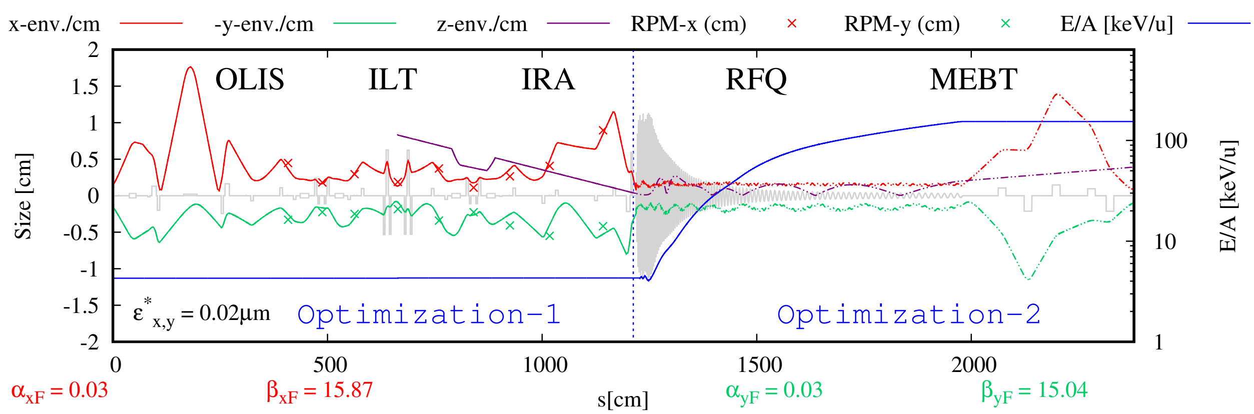

Figure 4: TRANSOPTR is used to find the source extracted distribution (Optimization-1) subject to transverse fit constraints consisting of the measured beamsizes at profile monitors. In Optimization-2, the model is used to compute the MEBT section quadrupoles necessary to cause a round waist at the location of the MEBT stripping foil, where the simulation ends, with dotted envelopes for the forward tune computation. Beam accelerates through the ISAC-RFQ from $E/A = 2.04$ keV/u to 153 keV/u. Final Twiss parameters shown at the bottom of the plot, with starting normalized emittance $\epsilon^*_{x,y}$. Longitudinal parameters chosen for an approximate z-focus into the RFQ, causing synchrotron oscillation, which TRANSOPTR has minimized. Scaled focal strengths of the elements are shown in grey for visual reference. Simulation ends on Fig. 1, A.

MODEL COUPLED ACCELERATOR TUNING

Beam profiles in one section can be used by the model to compute the tune in a forward section. Figure 4 shows measured beamsizes in the low energy section (Fig. 1, *LEBT*) used to first find the initial σ-matrix at the OLIS terminal given the realtime tune (Fig. 4, Operation-1). Next, a forward tune computation finds the magnetic quadrupole setpoints in the MEBT section required for a round beamspot at the location of the stripping foil (same fig., Operation-2). This includes model simulation and optimization of the envelopes through the ISAC-RFQ. This method is general and can be applied to any device in TRANSOPTR. The finding of the initial source extracted beam parameters and subsequent computation of optimized tune through the RFQ and into MEBT can be automated in software, using the sequential optimization method. In such a scheme, the operator controls the beam by supplying the diagnostic inputs, then selecting which particular model operation to perform:

1. Fitting initial beam conditions to measured profiles
2. Re-optimizing optics in measurement section
3. Model-computing optics in forward sections

The first case enables imaging of the source parameters using the beam transport system. The second case enables correction of the tune for example in cases where the source distribution changes unexpectedly. Finally, the third case enables computation of the downstream optics based on the measured on-line conditions, providing responsive and flexible tune computations for the linac. In any case, beam transmission through the low energy section's profile monitors must be high. Alternatively, the model can be supplied σ-matrix values using a tomographic method[6], providing multiple means to measure the beam matrix on-line.

OUTLOOK

Together with the variable energy ISAC-DTL autofocusing capability reported in [4] and ongoing work at the ISAC-II linac[7], the methods of model coupled accelerator tuning are being developed at TRIUMF, additionally informing future beam diagnostic needs. This includes the exploration of machine learning, which complements this work by using a neural network to perform beam centroid corrections.

REFERENCES

[1] R. Baartman, " TRANSOPTR Reference Manual," TRIUMF, Tech. Rep. TRI-BN-22-08, 2022.

[2] F. J. Sacherer, "Rms envelope equations with space charge.," *IEEE Trans. Nucl. Sci.*, vol. 18, pp. 1105–1107, 1971. doi:10.1109/TNS.1971.4326293

[3] O. Shelbaya, R. Baartman, and O. Kester, "Fast radio frequency quadrupole envelope computation for model based beam tuning," *Phys. Rev. Accel. Beams*, vol. 22, no. 11, p. 114 602, 2019. doi:10.1103/PhysRevAccelBeams.22.114602

[4] O. Shelbaya *et al.*, "Autofocusing drift tube linac envelopes," *Phys. Rev. Accel. Beams*, vol. 24, p. 124 602, 12 2021.

[5] O. Shelbaya and P. Jung, " Generation of TRANSOPTR files with xml2optr," TRIUMF, Tech. Rep. TRI-BN-22-06, 2022.

[6] O. Shelbaya *et al.*, "On-Line Retuning of ISAC Linac Beam with Quadrupole Scan Tomography," in *Proc. IPAC21*, 2021. doi:10.18429/JACoW-IPAC2021-THPAB205

[7] S. Kiy, R. Baartman, O. Kester, and O. Shelbaya, "First Tests of Model-Based Linac Phasing in ISAC-II," in *Proc. HIAT'2022 (in-press)*, Darmstadt, Germany, Jun.-Jul 2022.