Model Coupled Accelerator Tuning With an Envelope Code

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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. 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.

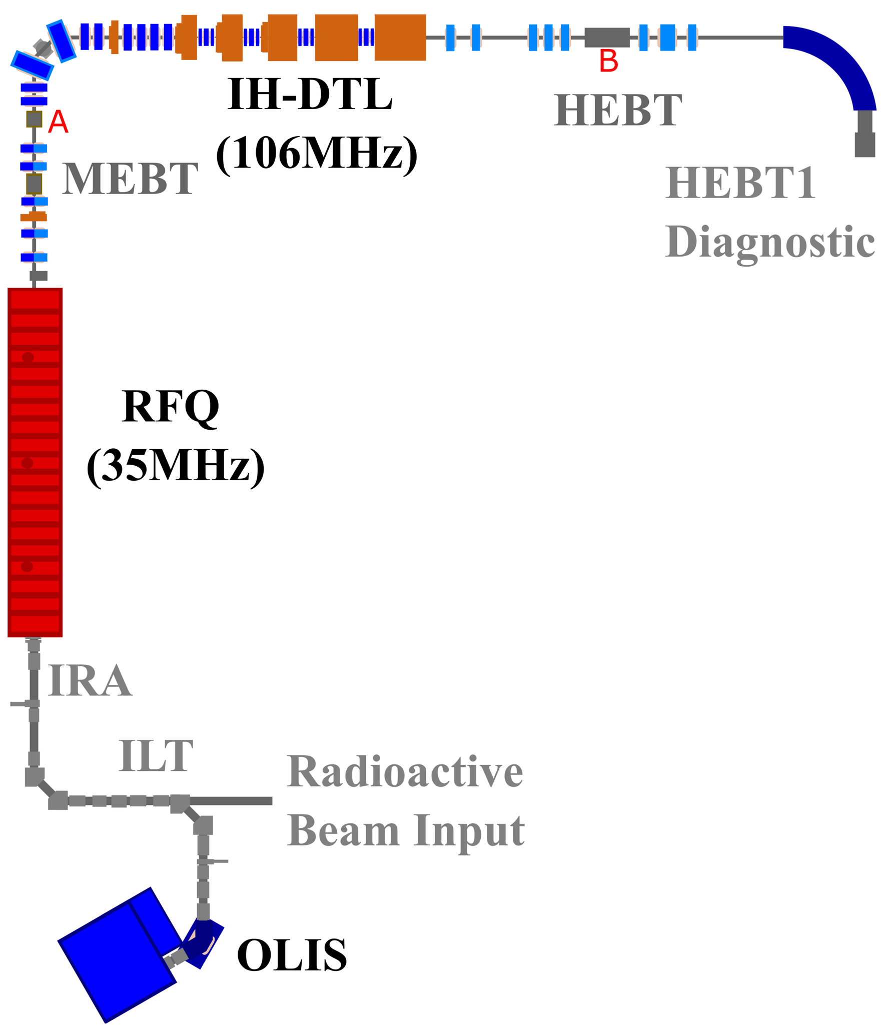

Figure 1: Schematic representation of the ISAC linac at TRIUMF. A & B are stripping foil locations

Envelope Model

TRANSOPTR[1,2] uses a sliding (Frenet-Serret) reference particle frame, shown below:

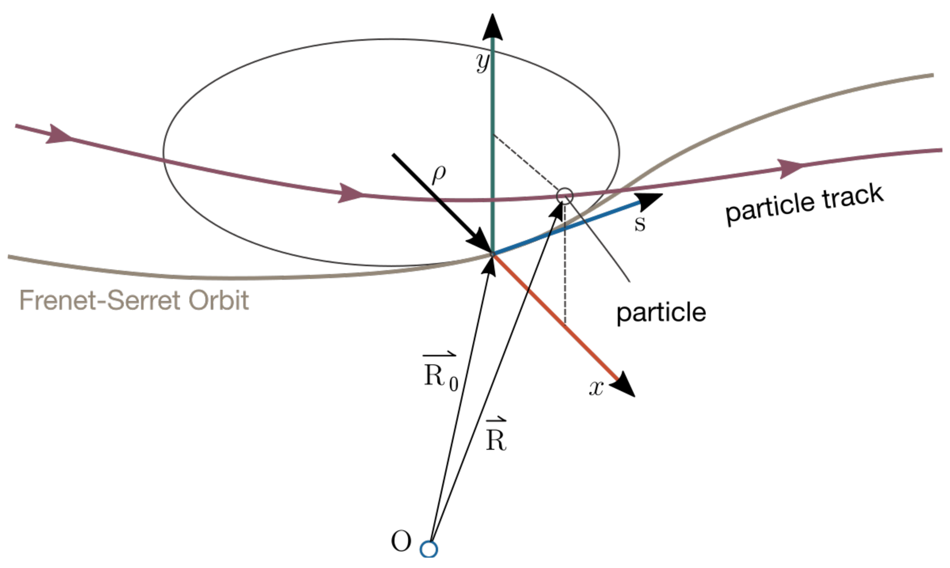

Figure 2: Sliding Frenet-Serret coordinates.

The transfer matrix for an small step ds along the trajectory is: $\mathbf{M} = \mathbf{I} - \mathbf{F}(s)ds$; $\mathbf{I}$ is the identity and $\mathbf{F}(s) = \mathbf{J}\mathbf{H}(s)$. $\mathbf{J}$ is the elementary symplectic matrix. $\mathbf{H}(s)$ is the Hessian matrix of the Hamiltonian.

We track the **beam covariance matrix** $\sigma(s)$ which contains the second moments of the beam distribution. The **envelope equation**:

$$\frac{d\sigma}{ds} = \mathbf{F}(s)\sigma + \sigma\mathbf{F}(s)^{\mathrm{T}}$$

allows tracking of the second moments along the trajectory. For a 6-D distribution (x, P_x, y, P_y, z, P_z), this represents 21 differential equations, plus energy and time for the reference:

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

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

Finally, $(z, P_z) = (\beta c\Delta t, \Delta E/(\beta c))$ in TRANSOPTR.

Optimization with Constraints

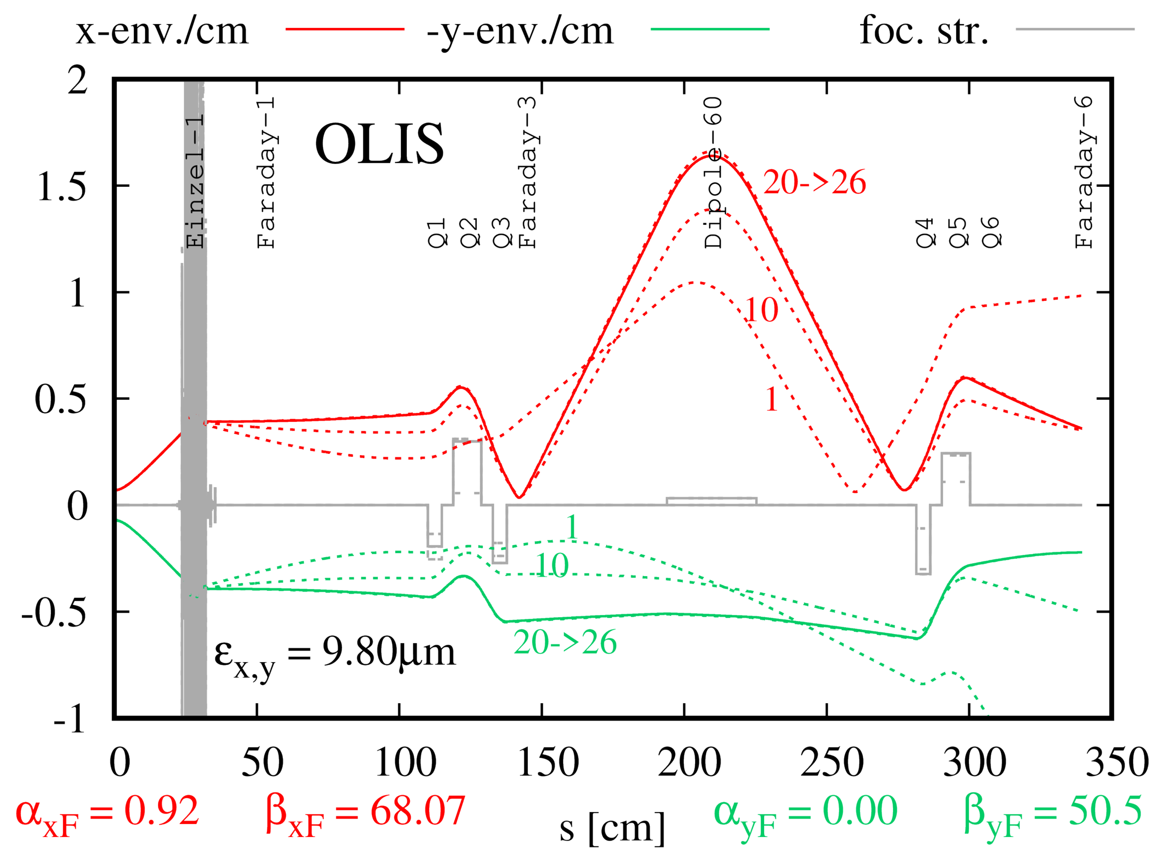

Figure 3: TRANSOPTR 2rms envelope optimization. Optimum Einzel lens (s~25cm) and 5 quadrupoles set points are found to produce the requested Twiss parameter match at the simulation end. After 26 iterations, the optimum set points are returned from the optimizer. All files have been automatically generated from an element position repository. Units of β are cm/rad.

Sequential Tune Optimization

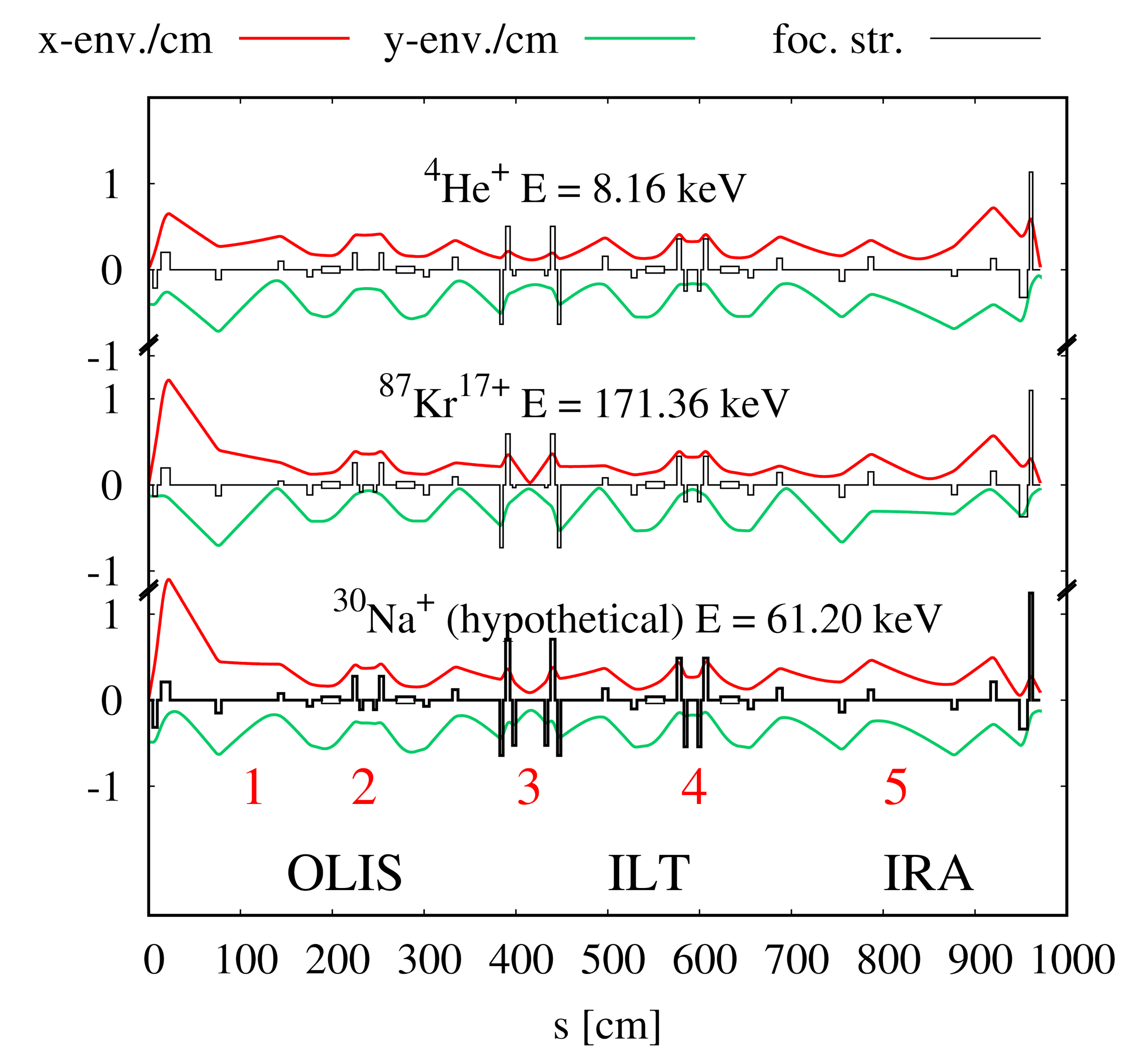

Figure 4: TRANSOPTR sequentially finds tunes in under 60 seconds, by breaking up long sequences into sub-segments with 4-6 optimization variables. This allows us to compute full linac tunes from first principles for on-line tuning. All files autogenerated.

Model Coupled Accelerator Tuning

Beam profiles in one section can be used by the model to compute the tune in a forward section, for to a specific source extracted beam distribution. By breaking the sequence into sub segments and sequentially optimizing small groups of variables, TRANSOPTR can be used to dynamically re-compute machine tunes, using diagnostic inputs (Fig.4).

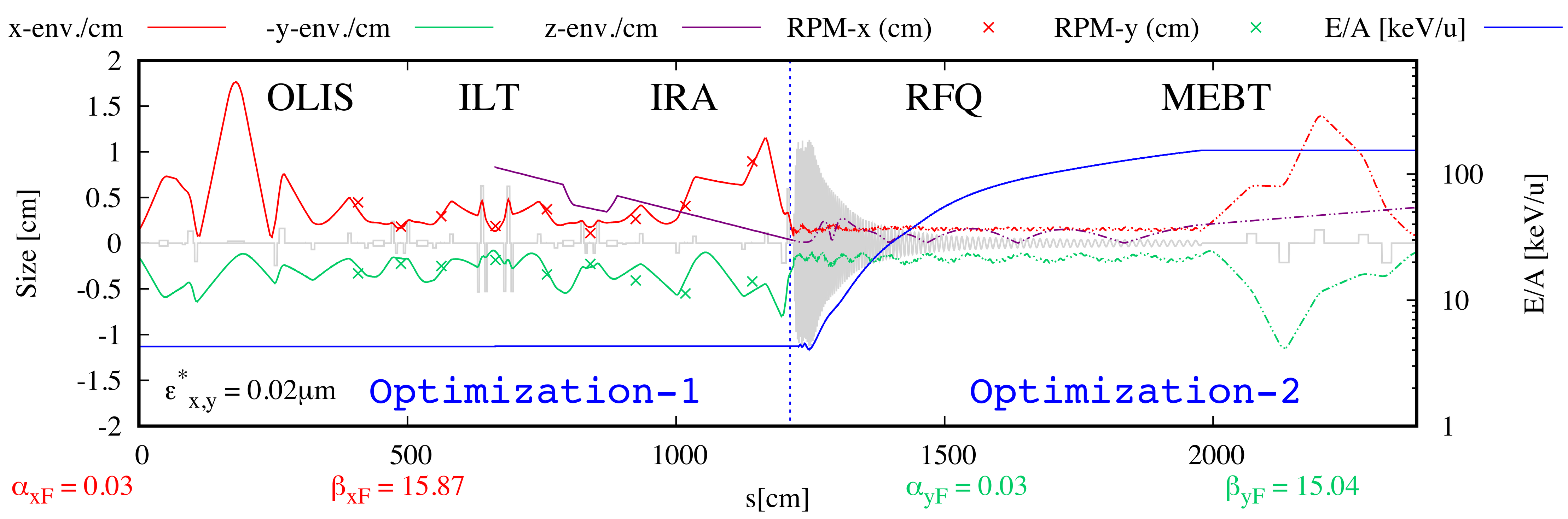

Figure 5: TRANSOPTR finds the source extracted distribution (Optimization-1) [3] subject to transverse constraints consisting of profile monitor beam-sizes. In Optimization-2, the model is used to compute the MEBT section quadrupoles to cause a round waist at the location of the MEBT stripping foil, where the simulation ends, with dotted envelopes for the forward tune computation. Beam accelerates through the ISAC-RFQ from 2.04keV/u to 153keV/u [4]. Final Twiss parameters shown at the bottom of the plot, units of β are cm/rad.

Outlook

Together with the variable energy ISAC-DTL autofocusing capability reported in [5] and quadrupole scan tomography [6], along with ongoing work at the ISAC-II linac [7], the methods of model coupled accelerator tuning are being developed at TRIUMF.

This includes the exploration of machine learning, which complements this work by using a neural network to perform beam centroid corrections.

This comes hand-in-hand with upcoming beam diagnostic upgrades, whose specifications are being informed using the envelope model shown herein.

References

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[6] O. Shelbaya, R. Baartman, P. Jung, O. Kester, S. Kiy, T. Planche Y.-N. Rao and S. Rädel, "On-Line Retuning of ISAC Linac Beam with Quadrupole Scan Tomography," *Proc. IPAC'21*, 08 2021.

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Discovery, accelerated