ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPG87

# AUTOFOCUSING ACCELERATOR BEAMS*

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*Abstract*

A novel tuning approach, Model Coupled Accelerator Tuning (MCAT), has been applied to the separated function DTL at TRIUMF's Isotope Separator and Accelerator (ISAC) [1]. A digital twin of the rare-isotope postaccelerator is used for transverse and longitudinal tune optimizations, which are then loaded directly into the control system. Beam-based testing produced accelerated beam with a 0.26% error in output energy, with a 1.6% energy spread. This method significantly reduces the operational complexity of tuning interventions, rendering them more efficient. An analysis of the high energy beam lines (HEBT) is also presented, including analysis of dispersive couplings in certain sections of the beamline. A mitigation strategy involving buncher cavities is discussed.

## INTRODUCTION

Reproducability is a cornerstone of the scientific method. Reliable scientific results come from controlled understanding of every element of the experiment. Investigations into fundamental physics, nuclear physics, astrophysics, and material science at TRIUMF-ISAC are fueled by heavy-ion beams, produced from ISOL targets bombarded by the 520MeV cyclotron proton beam, re-accelerated by the post-accelerator chain. Minimizing tuning time is increasingly important to ensure maximal experiment time in schedules; however, that should not need to come at the cost of relaibility.

The ISAC accelerator complex, shown in Fig.1, houses a series of post-accelerators which supply a rare isotope beam to the high energy experiments. These include three sequential accelerators: the ISAC radio-frequency quadrupole (RFQ), the inter-digital H-mode (IH) drift tube linac (DTL), and the superconducting radio frequency linac (SCRF). Both the DTL and SCRF are variable energy machines.

The DRAGON and TUDA experiments are the primary recipients of DTL beams below maximum energy. These nuclear astrophysics experiments investigate nuclear processes that drive stellar nucleosynthesis, and ultimately determine the elemental abundances we see around us.

Using the envelope code TRANSOPTR [2] an end-to-end simulation has been applied to tune the high-energy section at ISAC I. The Model Coupled Accelerator Tuning (MCAT)[3, 4] framework provides three main capabilities:

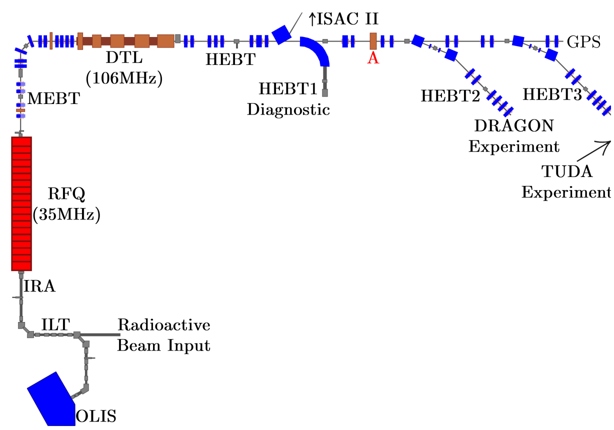


Figure 1: High energy complex at ISAC, where MCAT has been deployed. HEBT 11MHz and 35MHz bunching cavities located at "A".

1. Fitting initial conditions to measurements
2. Optimizing elements to produce desired optics
3. Computing forward optics for subsequent sections

## ENVELOPE MODEL

This model describes the emergent phenomena of the envelope as it relates to a reference particle traveling along it's path, $s$, in the Frenet-Serret coordinate system. Using this system we can define a vector to represent each particle in canonical coordinates:

$$\mathbf{X} = (x, P_x, y, P_y, z, P_z)^T, \tag{1}$$

and assuming the first moments are zero, the second moments, or the beam matrix, can be defined as:

$$\sigma \equiv \frac{1}{N}\sum_{n=1}^{N} \mathbf{X}\mathbf{X}^{\mathbf{T}}, \tag{2}$$

with $N$ particles. Evaluating Hamilton's equations on the Courant-Snyder Hamiltonian, and assuming the reference particle travels along the optical axis, one can linearize the equation of motion to:

$$\frac{d\mathbf{X}}{ds} = \mathbf{F}(s)\mathbf{X}. \tag{3}$$

The $\sigma$-matrix transformation is found by taking the $s$ derivative of eq. 2. Using eq. 3 the so-called envelope equation is defined as:

* We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC), [SAPPJ-2023-00038].
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ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPG87

$$\frac{d\sigma}{ds} = \mathbf{F}(s)\sigma + \sigma\mathbf{F}(s)^T. \quad (4)$$

Whereas the **F** matrix describes continuous transformations, the **M** transfer matrix describes point-to-point transformations:

$$\sigma_f = \mathbf{M}\sigma_i\mathbf{M}^T, \quad (5)$$

and itself transforms as:

$$\frac{d\mathbf{M}}{ds} = \mathbf{F}(s)\mathbf{M}. \quad (6)$$

TRANSOPTR uses an initial distribution $\sigma_0$, and an $\mathbf{F}(s)$ matrix for each element, to solve for the $\sigma$ and $\mathbf{M}(s)$ at each point by numerically solving the envelope equation.

The standard **F**-matrix for the IH-DTL is the axially symmetric linac matrix derived in [5], where here the on axis field, $\mathcal{E}(s)$, was generated using Opera2D [6, 7].

Using this model, the DTL longitudinal tune can be solved with 8 optimizations (5 IH tanks and 3 bunchers) of $(\phi, V)$ pair, followed by the 4 triplets for the transverse tune, using the TRANSOPTR function `linac`. This diminishes algorithm performance through solving for the longitudinal tune, slowing down tuning time for energy changes [8]. This laborious method is not necessary if we instead only focus on the transverse dynamics. Configuring the rf phase parameter such that $M_{65} + M_{43} + M_{21} \approx 0$, [9]the cavity can be essentially treated as a drift. This ignores the longitudinal dynamics, and models the cavity as a step function increase in energy with the TRANSOPTR function `rfgap`. The **F**-matrix for the *autofocus* method is simplified to:

$$\mathbf{F}(s) = \begin{pmatrix} 0 & \frac{1}{P_0} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{P_0} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{\gamma^2 P_0} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}. \quad (7)$$

## APPARATUS

The variable energy DTL, unlike a driver linac, must operate at a range of intensities, charge states, masses, and optput energies. Accepting beam at 2 ≤ A/Q ≤ 6, the DTL accelerates beam from the RFQ energy of 150keV/u up to 1.8Mev/u. Changing the output energy of the DTL requires adjusting both the phase and amplitude of the cavities. Operators can't read out the energy change until the new transverse optics are set for target energy and the transport section is tuned to the energy diagnostic. Operators must repeat this entire procedure to check the energy while performing beam energy changes by hand.

Experiments sometimes need frequent energy changes during beam delivery to measure different energy dependant nuclear properties.

In the medium energy (MEBT) corner of the ISAC beamline the high transverse beam distribution eccentricity following the stripping foil [10] necessitates a a corrective DTL injection matching procedure [3]. Performing energy changes with the autofocus methodology, it is thus necessary to set the transverse optics of the DTL and HEBT with the MCAT computed setpoints and manually detune the MEBT section instead [8]. This would substitude manually retuning the accelerator.

## MODEL COUPLED ACCELERATOR TUNING

Using the envelope model, live beam conditions can be easily read, modeled, and used to tune. This gives the ability to quickly update a live display of the beam envelope for operator usage. The parallel modeling approach has removed complexity in the tuning process, and increases repeatability and performance.

Readings from the rotary profile monitors (RPMs), are used with the parallel model to extract the initial beam distribution in the system. These are used as data to fit the initial contitions, $\sigma_i$, an example of this is shown in Fig. 2, and the intitial conditions are shown in Fig. 3. This further enables first order simulations of the beamspot at the experiment's target, enabling on-line monitoring of beamspot attitude and size. Dynamic on-line updates can be made to show live conditions as optics are adjusted, taking approximately one second to update. Beyond this, initial conditions can be used in a separate optimization to produce, for example, a new beam spot size at the experiment's target chamber [4].

The rapid parallel model updates are essential to tuning the MEBT-DTL section. Development shifts have been used to solidify this method. This method elaborated herein means the DTL can be quickly set to change energy. Developmental tests have achieved 0.26% difference from the theoretical energy value with a 1.6% energy spread at a beam energy of 1.53MeV/u, however note that the energy measurement contains an up to 1% error [1, 9].

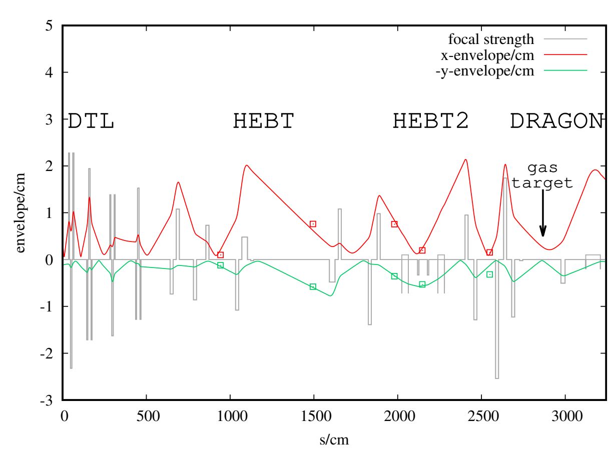


Figure 2: 2rms beam envelope fit to RPM profile measurements with $^{12}C^{3+}$ beam accelerated from RFQ energy, E/A=150keV/u, to E/A=1.53Mev/u, and delivered to the DRAGON experiment. The new autofocus methodology is used to model the DTL.

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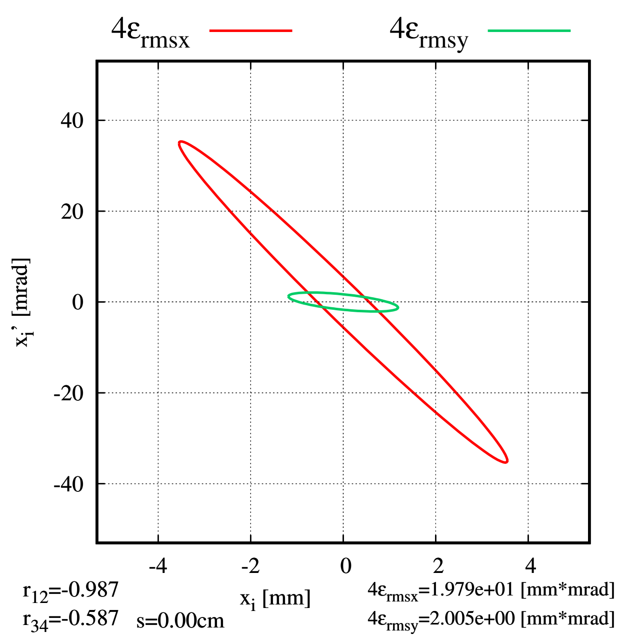


Figure 3: Phase space ellipses showing the fitted initial conditions from Fig. 2. Shows extreme eccentricity in the (x,x') distribution exiting the MEBT section.

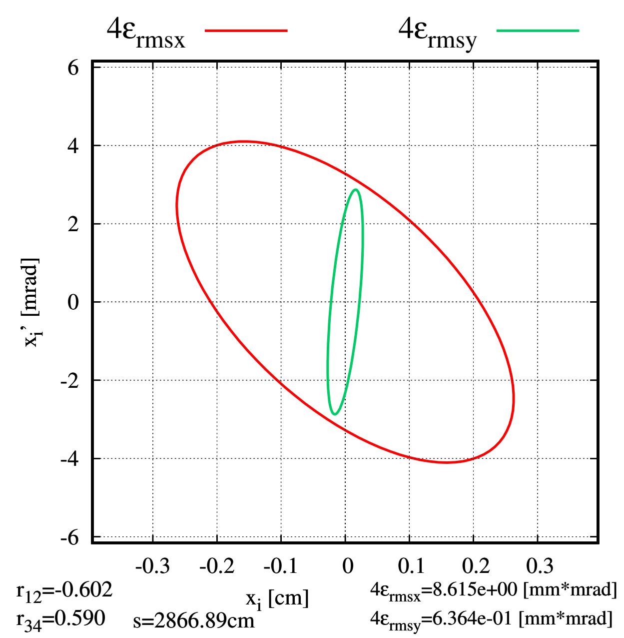


Figure 4: Phase space ellipses showing the distribution of beam delivered to DRAGON at the gas target labeled in Figure 2.

Previously an 8 hour shift could be needed to adjust energy, forcing experimenters to trade between collecting more data at a given beam energy, or risk losing time for an energy change. Autofocused energy changes unlock extra time for experiments, and using the envelope model the beam distribution can be predicted and set at the experiment. Figure 4 shows the phase space ellipses produced at the DRAGON gas target, labeled in Fig. 2.

MCAT development showed that the high energy (HEBT) corners, HEBT2 and HEBT3, induce a chromatic coupling [11]. While the design tune around the HEBT corners is *singly*-achromatic, they are not *doubly*-achromatic. This means the transfer matrix element $M_{16}$, linking $(x, x')$ with $(z, z')$, is zero at the exit of the corner, but sharply slopes out of the corner. Figure 5 shows both the original T3D design tune for the achromatic bend and the `TRANSOPTR` reconstruction which provides the data on $M_{16}$.

This correlation between longitudinal divergance ($z' = \Delta E/(\beta c)$) means as $\Delta E/E$ increases, transmission through the 8mm diameter aperture of the DRAGON gas target decreases. As $\Delta E/E$ reaches 1%, the transmission drops to 75% [11]. This effect can be mitigated through use of the MEBT bunch rotator, the HEBT bunchers, and setting an energy focus at DRAGON. However it can not be removed in the traditional sense with the quads between the bends, as they are underpowered and have the incorrect polarity[11].

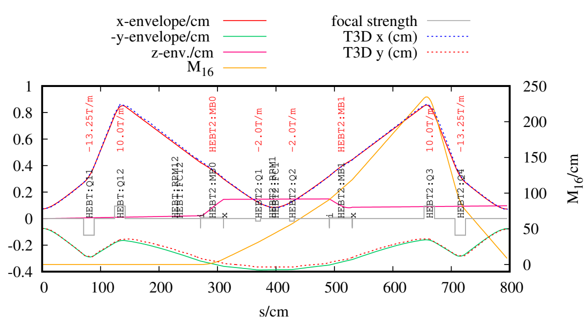


Figure 5: Achromatic design tune from [12] and T3D simulation form [13] for the HEBT 45° bend. Beam is A/q=6 and E/A=1.5MeV/u.

## NEXT STEPS

MCAT provides the framework to develope new techniques involving energy changes using methods developed in [1]. This shows promising possibilities for using the DTL to lower beam energy below RFQ energy, change beam energy delivered to DRAGON with the HEBT 11 and 35MHz bunchers (labeled "A" in Fig. 1), and sweeping energy while scaling optics. This provides exciting new avenues for nuclear physics research into resonances below typical DTL energy, and energy sweeps for direct capture charactirazation and resonance discovery.

Alongside MCAT, the Bayesian optimizaion for ion steering (`BOIS`) method has been developed at TRIUMF for automated steering[14].

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