AUTOMATIC TRANSVERSE AND LONGITUDINAL TUNING OF SINGLE AND MULTIPLE CHARGE STATE ION BEAMS*

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Abstract

Extensive end-to-end beam dynamics simulations of the RIA driver linac using the code TRACK and including all sources of machine errors and detailed beam loss analysis showed that the losses could be significantly reduced for a fine-tuned linac. For this purpose we have developed an automatic longitudinal tuning procedure for multiple charge state heavy-ion beams. For a complete tuning tool, we have recently developed an automatic transverse tuning procedure to produce smooth transverse beam dynamics by minimizing the RMS beam sizes after each focusing period. In addition to improving an existing tune, this powerful automatic beam tuning tool can be used to retune the linac and restore the beam after one or more elements failures and to develop new tunes for ion beams with different Q/A ratios.

INTRODUCTION

In most existing accelerators, beam tuning or retuning after an element failure or to change the beam parameters or specie is usually done manually step by step. This is due to the lack of a realistic model of the machine that could fully support the machine operations which often results in excessive time wasted in beam tuning. The ultimate goal of this effort is to produce automatic and realistic beam tuning tools that could be incorporated into a realistic beam dynamics code which could be used for machine operations. In this study we focus on proton and heavy-ion linacs.

In a previous work [1] we have developed an automatic longitudinal tuning procedure for multiple charge state heavy-ion beams. The procedure was used to fine tune the medium-β section of the Rare Isotope Accelerator (RIA) driver linac which has significantly reduced the beam losses in the subsequent high-energy section of the linac. The same procedure was also used to retune the beam after one or more cavity failure and restore the beam with limited beam loss. This procedure is now incorporated into the beam dynamics code TRACK [2]. TRACK is a ray-tracing code that was originally developed to fulfill the special requirements of the RIA accelerator systems [3]. It is, however, a general beam dynamics code for hadron linacs (protons and heavy-ions) design and simulation. The most recent version of TRACK supports an extensive number of different types of beam line elements with 3D fields including fringe fields. 3D space charge forces for intense beams are included by solving the Poisson equation of the beam after every tracking step. It also includes the simulation of all possible sources of machine errors, beam monitoring tools, corrective transverse steering and longitudinal corrections. TRACK was extensively used for large scale end-to-end beam dynamics simulations of the RIA driver linac including all sources of machine errors and detailed beam loss analysis [4].

For a complete tuning tool, we have recently developed an automatic transverse tuning procedure to produce smooth transverse beam dynamics by minimizing the RMS beam sizes after each focusing period. After reviewing the main results of the automatic longitudinal tuning procedure, we present the method and results of the transverse tuning procedure. Possible application for real machine operations is also discussed.

AUTOMATIC LONGITUDINAL TUNING

The beam tuning procedure involves the optimization of beam line element parameters to realize certain beam conditions. The criteria may depend on the accelerator lattice and the desired beam parameters. In the case of the RIA driver linac for example it was essential to minimize the longitudinal beam emittance before the stripper in order to limit beam losses in the subsequent section. The optimization parameters in this case were the synchronous phases and field amplitudes of all the cavities located in the medium-β section of the linac. In order to realize these conditions, the beam centers in both energy and phase of all charge state beams need to converge to the same center as the reference charge state beam. In addition the beam ellipses or Twiss parameters need to be matched to have the same orientation in the longitudinal phase space and ensure a minimal total beam emittance. The method is described in more details in the original paper [1].

Figure 1 shows the evolution of the energy and phase centers of a 5 charge state uranium beam along the medium-β section of the RIA driver linac before and after applying the automatic tuning procedure. It is clear that all beams converge to the same center at the end of the section right before the second stripper. Figure 2 shows the corresponding beam ellipses at the end of the section. By matching both the centers and orientations of all beam ellipses, the overall emittance was reduced by a factor of 2 or more. As a result, the beam losses in the subsequent high-energy section were reduced by about a factor of 3 as shown in figure 3.

AUTOMATIC TRANSVERSE TUNING

The transverse tuning procedure consists of producing smooth transverse beam dynamics by optimizing the field

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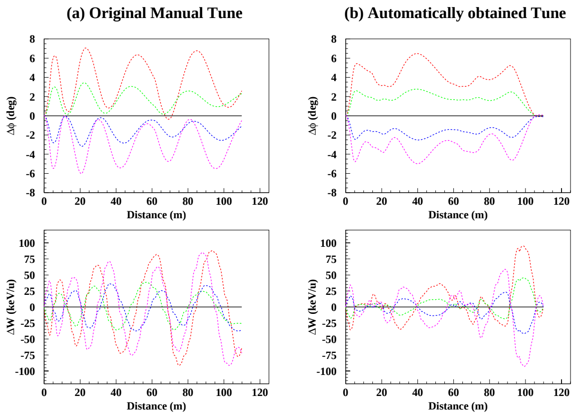
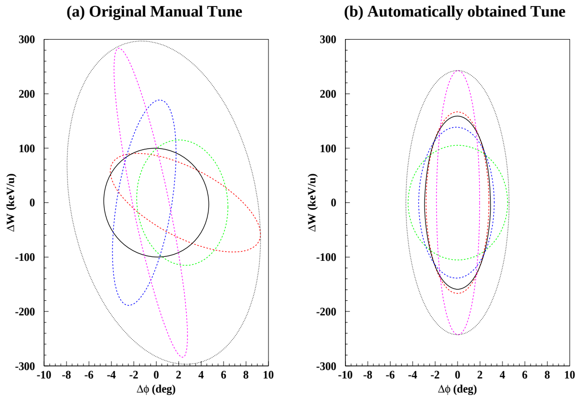

(a) Original Manual Tune

(b) Automatically obtained Tune

Figure 1: Beam phase and energy centroid deviations for the different charge states (dashed curves) with respect to the reference charge state (solid line) plotted as function of distance along the medium-β section of the RIA driver linac.(a) For the original manual tune and (b) for the automatically obtained tune.


(a) Original Manual Tune

(b) Automatically obtained Tune

Figure 2: Beam ellipses just before the second stripper for both (a) the original manual tune and (b) the automatically obtained tune. The solid ellipse corresponds to the reference charge state, the dashed ones are for other charge states and the larger dotted ellipse represents the effective emittance of the multiple charge state beam.

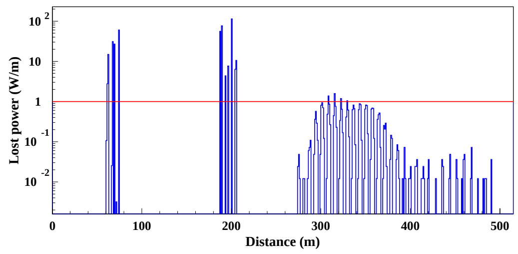
strengths in the focusing elements. This is done by minimizing the fluctuations in RMS beam sizes along the considered section. Large fluctuations in the RMS beam sizes are usually induced by mismatch between sub-sections of the linac which could eventually lead to instability of particle motion and beam losses. This method is general and should produce good results for both regular (periodic) or non regular accelerating structures.

The function to minimize in this case is:

$$F = X^0_{rms} + \sum_i \frac{(X^i_{rms} - X^0_{rms})^2}{\epsilon^2_{X_{rms}}} + Y^0_{rms} + \sum_i \frac{(Y^i_{rms} - Y^0_{rms})^2}{\epsilon^2_{Y_{rms}}}$$

where X^0_{rms} and Y^0_{rms} are the RMS beam sizes at the entrance of the section or after the first focusing period, the sum index i runs over the focusing periods in a given section and $\epsilon_{X_{rms}}$ and $\epsilon_{Y_{rms}}$ are the allowed errors on the RMS beam sizes. In the case of a multiple charge state beam we use the parameters of the total beam. The procedure could very well be used for a single charge state beam. A similar procedure could be implemented to smooth out the longitudinal beam parameters if needed. The minimization is performed using the CERN-LIB optimization package MINUIT [5] modified to consider a large number of fit parameters. The fit parameters in this case are the magnetic field strengths of all focusing elements in the section.

(a) Original Manual Tune



(b) Automatically obtained Tune

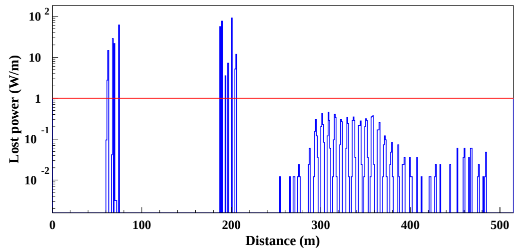


Figure 3: Beam loss in Watts/m along the RIA driver linac for both (a) the original manual tune and (b) the automatically obtained tune. The horizontal line corresponds to the 1 Watts/m limits suggested for hands-on maintenance. The first two clusters of losses at the location of the first and second stripper, respectively, are controlled losses. The scattered losses in the high-β section of the linac are uncontrolled losses. From (a) to (b) we notice that both the total and peak losses are reduced significantly.

Figure 4 shows the X- and Y-rms beam sizes before and after applying the automatic tuning procedure. We clearly notice the reduction in the fluctuations of the RMS beam sizes; the low-frequency oscillations due to beam mismatch was removed after applying the tuning procedure. In this case the tuning is done for a two-charge state uranium beam in the first section of the RIA driver linac by tracking a small number of particles (typically 100 for each charge state) using the code TRACK. Space charge forces are negligible in this case. The matrix approach like in TRACE-3D [6] didn't produce good results because of significant deviations when performing full beam dynamics simulations using realistic 3D fields. Tuning is done better by tracking a large number of particles through realistic 3D and space

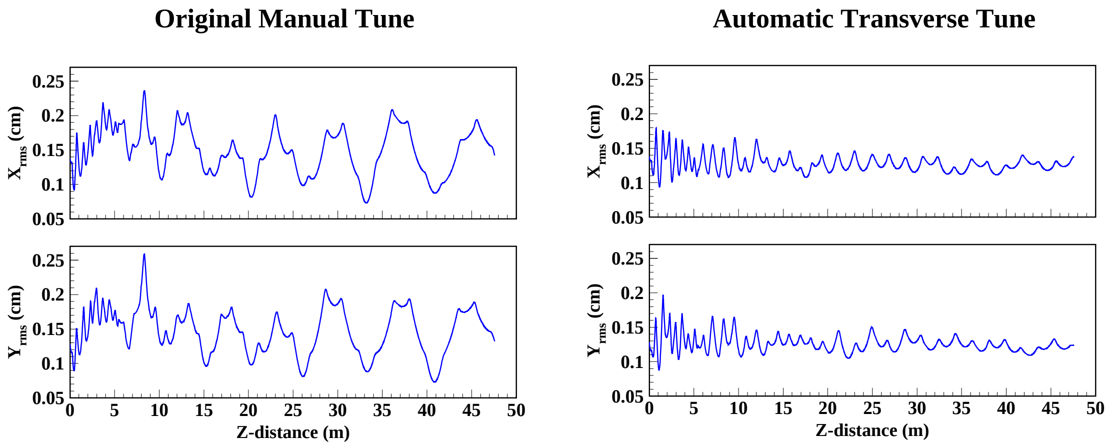


Figure 4: X- and Y-rms beam sizes before and after applying the automatic transverse tuning procedure. The beam is a two-charge state uranium beam in the first section of the RIA driver linac.

charge fields. In the case where space charge forces should be included, the typical number of particles would be at least 10^5. Since the optimization process involves multiple iterations, large scale computing will be required.

POSSIBLE APPLICATION FOR REAL MACHINE OPERATIONS

For experimental realization on a real machine, the automatic longitudinal tuning procedure discussed above would require the measurement of the absolute energy of the reference charge state, the energy and phase deviations with respect to the reference charge state as well as the Twiss parameters for individual charge state beams. We acknowledge that these quantities are not easy to measure even for a single beam calling for more research and development in this particular direction.

In this case we propose to perform separate measurements for the individual charge state beams by selecting a given charge state at the first stripper (entrance of the medium-β section). The beam energy and phase centroids could be measured accurately using the time-of-flight method as presented in [7] where an accuracy of 10^{-4} for both energy and phase was reported. The beam energy width could be measured precisely using the dipole magnet downstream of the second stripper. A bunch time detector similar to the one presented in [8] could be used to measure the phase width right after the buncher located in the middle of the chicane area downstream of the second stripper. At this location the phase width is at its largest value and the 20 ps resolution of such device may provide a reasonable measurement. The development of a bunch time detector based on X-rays instead of secondary electrons may reduce this time resolution to about 5 ps or better. Varying the phase of the last cavity in the section and performing multiple energy and phase width measurements would allow the determination of the longitudinal beam emittance and extract the Twiss parameters.

For the automatic transverse tuning procedure, beam measurements are usually easier although not possible at the end of every focusing period. In principle, the procedure could be easily adapted to use measurements at the available beam diagnostic devices on the machine.

These measurements will require fast real-time processing of the diagnostics data. Such rapid analysis and communication with the control system will be an important capability of our plan to implement a model-driven accelerator.

SUMMARY

We have successfully implemented and tested new automatic longitudinal and transverse beam tuning tools that could be incorporated into a realistic beam dynamics code. These tools are developed for application in real machine operations in the purpose of realizing the concept of the ”Model-Driven Accelerator” to reduce the time and cost of beam tuning in modern accelerators.

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