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Experimental test of an online ion-optics optimizer

A.M. Amthor[a,*], Z.M. Schillaci[a,1], D.J. Morrissey[b], M. Portillo[c], S. Schwarz[b], M. Steiner[b], Ch. Sumithrarachchi[b]

[a] Department of Physics and Astronomy, Bucknell University, Lewisburg, PA, 17837, USA
[b] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA
[c] Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA

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ABSTRACT

A technique has been developed and tested to automatically adjust multiple electrostatic or magnetic multipoles on an ion optical beam line – according to a defined optimization algorithm – until an optimal tune is found. This approach simplifies the process of determining high-performance optical tunes, satisfying a given set of optical properties, for an ion optical system. The optimization approach is based on the particle swarm method and is entirely model independent, thus the success of the optimization does not depend on the accuracy of an extant ion optical model of the system to be optimized. Initial test runs of a first order optimization of a low-energy (<60 keV) all-electrostatic beamline at the NSCL show reliable convergence of nine quadrupole degrees of freedom to well-performing tunes within a reasonable number of trial solutions, roughly 500, with full beam optimization run times of roughly two hours. Improved tunes were found both for quasi-local optimizations and for quasi-global optimizations, indicating a good ability of the optimizer to find a solution with or without a well defined set of initial multipole settings.

1. Introduction

Ion optical systems are critical to the success of nuclear physics research programs at laboratories around the world [1]. Flexible ion optical systems include tunable elements to allow operation at different magnetic or electric rigidities and in different modes to be useful for a variety of experiments (e.g. to efficiently collect the products of different reaction mechanisms [2] or to operate in dispersion matched [3,4] rather than dispersive mode) to experimentally address a wide range of physics questions.

Modern separators and spectrometers have been designed with large acceptances to transmit, separate and often analyze secondary beams or other reaction products of interest. They are able to achieve combinations of large acceptances – in angle, momentum (or energy), mass, and charge – while maintaining high A/Q resolving power (e.g. BigRIPS [5] at RIKEN, S^3 [6] under construction at GANIL, ARIS [7] under construction at FRIB, and SuperFRS [8] planned for FAIR). This is made possible because of their ability to produce and sustain high fields and field gradients in their constituent, large-bore ion optical elements and to superimpose multipole correction elements (e.g. sextupoles and octupoles) together with quadrupole focusing elements to allow the correction of higher order aberrations, which become more significant as larger phase space volumes are transmitted and would otherwise degrade resolution [9–11]. Higher current densities made possible by the use of superconducting materials increase the number of tunable multipole correction elements (e.g. sextupoles and octupoles) that may be practically included, thus increasing the number of degrees of freedom in the optical system.

Resolution is achieved by a combination of physical separation and detection. Physical separation – especially of the unreacted primary beam particles – is critical to reduce beam rates on detectors and beam line materials as far as possible to enable the highest possible primary beam intensities to be used for production of the nuclei of interest [12]. Multi-stage separators, comprised of many more beamline elements, are necessary in order to separate or identify the rarest events from the weakest reaction channels (e.g. [13]). Detailed system characterization combined with tracking detectors can allow trajectory reconstruction [4,14], to improve resolving power achievable through detection.

Separator and spectrometer systems' ion optical properties depend on the settings of their many adjustable field elements, which must be

* Corresponding author.
E-mail address: m.amthor@bucknell.edu (A.M. Amthor).
1 Present Address: Brandeis University, Martin A. Fisher School of Physics, Abelson 403, 415 South Street, Waltham, MA 02453, USA.

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tuned during operation to provide the necessary transmission, separation, and identification. The typical approach to tuning an ion optical beam line begins with the development of a detailed representation of the system in an ion optical model code (e.g. COSY Infinity [15] or GICO [16]). The multipole elements are modeled either based on detailed magnetostatic or electrostatic calculations [2] or based on careful measurements of the fields themselves [17].

The element field settings are optimized in the model system and the optimized tune is subsequently applied to the physical system. Even when considerable effort has been applied to develop a detailed optical model [18], inconsistencies between the physical system and the model invariably lead to deviations from the expected performance of the model-derived tune [14]. The model-derived tune is then manually adjusted during commissioning and subsequent operation [19] to improve performance to the level needed for experimental work. Under this approach, development of additional, specialized optical tunes represents a significant development effort on the part of the laboratory.

The online optimization technique presented here eliminates much of the investment in detailed model development beyond the construction phase and entirely eliminates the manual tuning step, replacing both with a computer-controlled phase of automated beam line optimization. For longer, modern separators with many degrees of freedom, the volume of tune space is so large that model-derived insight into the types of tunes likely to produce good performance is of more limited utility. Even a limited neighborhood around a model-derived tune can have a very large volume. A global optimization algorithm is therefore advantageous.

The particle swarm optimization (PSO) algorithm [20] is a global optimization algorithm that shows success in optimizing high-dimensional functions with a complex terrain [21]. PSO has been used successfully to optimize higher order optical tunes in the design phases of other ion optical systems, including S^3 [10] and ARIS [7]. Genetic algorithms (GA), another global optimization technique, have also been used extensively in computational ion optics optimizations, primarily in accelerators [22,23]. In both cases, previously published studies have considered only optimization of computational models of ion optical systems, where as the present work optimizes the physical ion optical system. GAs have the advantage that the weights of multi-objective optimizations may be assigned a posteriori [24], but the PSO technique has shown faster convergence [25]. For online optimizations, we prioritize convergence in fewer system evaluations and thus make use of the PSO technique.

Local optimization algorithms were not used in this study (even in simulations) because local optimizers are already known to fail – even in optical model calculations – for the specific problem which is the ultimate goal of this project, the simultaneous optimization of many degrees of freedom, where model-derived or other intuition into what tunes are likely to be successful is difficult to produce or unreliable. Nevertheless, the experimental technique being developed here would translate well to use with any other optimization algorithm, either global or local, since the experimental challenges being addressed are not necessarily specific to the optimization algorithm being used. Local optimizers may be beneficial in a final stage of optimization, after swarm convergence, but such techniques were not a priority for testing in the limited beam time available.

2. Methods

The online optimization approach consists of a computer-automated feedback loop (see Fig. 1 for a graphical overview) in which:

1. A controlling optimization algorithm selects and provides a set of element field settings (the tune, $\vec{X}_i$) to the beam line control system,

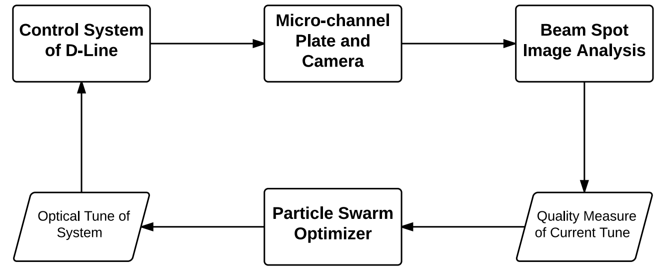

Fig. 1. A flow chart outlining the three-part online optimization approach described above. Labeled rectangles represent physical or computational objects while parallelograms represent information exchanged between the systems. The optimizer first sends a trial optical tune of the system (a single position vector in state space, discussed in the text as $\vec{X}_i$) to the experimental system. The results of the trial tune are then returned to the optimizer in the form of a quality measure (the objective function value) for the given tune. After several trial tunes are evaluated in this way, gathering all the desired information for the current full step of the optimizer, the optimization algorithm will produce a new set of trial solutions based on these results.

2. The control system reads in the settings and applies the tune to the beam line, changing the optical properties of the system as the elements reach their new field values, and
3. After a suitable delay, data collected from beam line detectors are analyzed to evaluate the quality of the provided tune, according to predefined criteria.

In this initial experiment only spot size and intensity (the best available proxy for transmission) at the end of the beam line were considered. Note that this represents a waist tuning rather than an image tuning approach. The quality of the tune, as determined in step 3 above, informs the future selection of trial tunes through feedback to the controlling optimization algorithm. Over time this process is repeated, resulting in settings with improved optical performance. After the evaluation of many tunes (in this case some hundreds of tunes), the optimizer will have converged to a particular region about an identified and well performing “global best” tune.

The swarm optimizer may be thought of as a method that finds a best position in solution space through the directed wanderings of a swarm of particles moving through that space. A mental picture often referenced is that of a swarm of bees searching for a source of pollen in three dimensional space. The bees mostly plan their movements autonomously, but some simple communication among swarm members is involved that can help swarm members to find the object of their wanderings. Thinking abstractly, a swarm consists of N independent swarm particles moving through n-dimensional state space, where the “position” of the ith particle in the swarm (the state $\vec{X}_i$ described in Eq. (1), for i from 1 to N) represents a particular tune of the n electric or magnetic elements along the beam line being optimized. In our experiment the optimizer tunes nine electric quadrupoles, so the full swarm consists of N nine-dimensional “position” vectors (the states $\vec{X}_i$) and corresponding velocity vectors ($\vec{V}_i$). Once each swarm particle’s initial state and velocity are randomly selected, the optimization proceeds by evaluating each member of the full swarm at its present position in state space, producing an objective function value for each $\vec{X}_i$ based on the performance of the tune, then evolving the swarm as described in the paragraphs below and in Eqs. (3), (4), and (5). The evaluation and evolution of all N swarm particles constitutes one full swarm iteration.

The number of swarm particles to use in the optimization is up to the user. In our runs, we initially used swarms with $N = 15$ and later with $N = 30$. Note the multiple lines of a given shade in each panel of Figs. 5 and 6, showing the evolution of each of the N swarm members as the optimizer evolves the swarm through the course of the optimization. Larger swarms will tend to produce more robust optimizations, since