RANDOM WALK OPTIMIZATION IN ACCELERATORS: VERTICAL EMITTANCE TUNING AT SLS

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Abstract

The high performance of an accelerator is realized through various model-based corrections utilizing beam measurements. These corrections are, however, limited by measurement errors as well as model deficiencies. To overcome these limitations and further push up the performance, we investigated the application of a random walk optimization (RWO) technique. An application to the coupling correction at the SLS was successful to significantly lower the vertical emittance even after elaborate model-based corrections were applied. The methodology of RWO and potential applications of the technique are discussed.

INTRODUCTION

The performance of an accelerator highly depends on the actual setting of parameters such as magnet currents and rf voltages. Although most of (or all) the accelerator components are characterized in the lab before installation, corrections of these parameters based on beam measurements are essential in practice to realize highest possible performance. Misalignments of components are also sources of performance degradation and must be compensated by available correctors.

These corrections are, however, limited as the correction approaches the ideal value because of measurement errors. The corrections are usually computed using a machine model, and thus model deficiencies may also be sources of the limitation. Although the model can be calibrated with the real machine, we cannot avoid measurement errors during the calibration, and therefore the correction is improved only when model deficiencies are dominant.

To overcome the limitation, an empirical tuning can be applied when a suitable target function is observable. An earlier work of this kind was performed at SLAC in the optimization of the luminosity at the PEP-II collider [1], where the relative beam position and angle of electron and positron beams were adjusted so as to maximize the luminosity. The optimization is relatively easy due to a small number of correction variables. However, it is noted that the luminosity is employed as the target function rather than the beam position monitor (BPM) readings to control beam orbits. For a larger number of correction variables, the downhill simplex method was examined at KEK to optimize the luminosity of the KEKB collider [2].

Although these methods require temporary detrimental variations to the instantaneous luminosity to determine the optimum solution, they can nevertheless be applied on-line in cases where the integrated luminosity is the primary concern. For the purpose of on-line optimization, it is preferable or even essential to ensure only small variations in the target function.

We investigated the application of a random walk optimization (RWO) technique, which may be one of the most suitable algorithms for accelerators in general. An application to the vertical emittance tuning at the SLS was indeed successful to considerably lower the vertical emittance even after elaborate model-based corrections were applied. We discuss the methodology of RWO together with the beam result and potential applications of the technique.

RANDOM WALK OPTIMIZATION

RWO is applicable when a suitable target function is observable and available on-line. The correction variables are slightly varied based on random numbers and, if fortuitously the target function is improved, the attempted setting remains in the machine. Otherwise it is removed before the next step is initiated. An optimum solution is finally found by iterating on this trial-and-error basis. A flowchart of RWO is shown in Fig. 1.

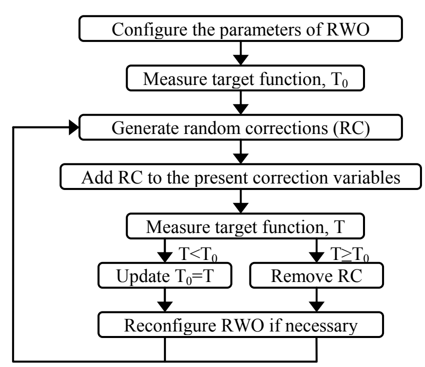

Figure 1: Flowchart of RWO for a minimization of target function T. RWO is parameterized by a random number distribution (usually Gaussian or uniform), the step size and a set of correction variables.

RWO is motivated by the following possible advantages.

- Adverse effects of high dimensionality are avoided.
- Optimization may converge rather quickly when applied in addition to a systematic correction.
- Compatibility with an on-line optimization.
- Implementation requires minimal effort.

The number of correction variables can be of the order of ten or even more. For those optimizations, a brute-force approach to scan all parameter space is not feasible because of the "curse of dimensionality", i.e. time to find the optimum solution is an exponential function of the number of correction variables. It is, however, able for RWO to efficiently find a successful step toward the optimum solution by varying all the correction variables in each step. RWO may be invoked after model-based correction(s), when the optimum solution is within "walking distance". To judge whether the attempted step is successful or not, it is sufficient to vary the target function comparably to its measurement resolution. Thus RWO may be utilized even during user operation / physics run to maintain the target function. Practically an implementation of RWO costs minimal effort.

Obviously RWO is a model-independent correction, and (small) calibration error of correctors may not be an issue. Although random walk and other algorithms are implemented into various accelerator computer codes, it is of interest to apply this concept to the real machine, where beam measurement errors are unavoidable and the machine model may include some deficiencies.

RWO has a lot of potential applications. One of them is the vertical emittance tuning in an electron storage ring as discussed in the next section. Damping rings in future linear colliders, e.g. ILC and CLIC, and circular colliders with sheet beams may profit from this technique to achieve smallest possible vertical emittance and maintain it during operation.

In storage rings, the beam lifetime is mostly determined by the unwanted excitation of resonances near to the operating point. The beam lifetime or equivalently the beam loss monitor signal can be a target function to be optimized using magnets such as skew quadrupoles and higher-multipoles, as correction variables.

A precise control of beam trajectory is required in some linear accelerators. The beam trajectory control can be complemented by RWO after applying beam-based alignment. For example, the electron beam trajectory in the undulator section of X-FEL facilities must be aligned with a precision of a few µm [3] to maintain a good overlap of the electron and photon beam. Once lasing is established, the averaged pulse energy of the laser may be available as a target function of RWO while dipole correctors (or reference points of BPMs in cases an orbit feedback is in operation) are used as the correction variables.

There may be other useful applications, where a suitable target function is available. In a tuning that requires an optimization of several beam parameters at the same time one can employ a "super target function" composed from several quantities of different nature.

APPLICATION TO VERTICAL EMITTANCE TUNING AT SLS

The vertical equilibrium emittance in an ideal flat lattice, due to the direct recoil of emitted photons, is very small. At the SLS, this value is ~0.2 pm·rad. In a real lattice with magnet errors, skew quadrupole components and vertical dipolar fields, which mostly originate from the physical misalignment of magnets, betatron coupling and vertical dispersion are created, leading to a vertical emittance in the order of several pm·rad to tens of pm·rad.

At the SLS, a vertical emittance of ~1.8 pm·rad was established in March 2011 by model-based corrections: Betatron coupling and spurious dispersion were measured form the orbit responses at the BPMs to variation of the dipole correctors and the rf frequency. The 24 non-dispersive and 12 dispersive skew quadrupole correctors are employed for correction [4]. The vertical emittance is monitored on-line by a beam size monitor [5].

In April 2011, a girder realignment campaign was initiated in order to mainly suppress the source of vertical spurious dispersion and consequently lower the emittance [6]. Finally a vertical emittance of ~1.3 pm·rad was achieved through the magnet girder realignment and the model-based corrections.

We applied RWO in addition to the model-based corrections. Since the ratio of vertical to horizontal emittance is quite small (0.024 % for a horizontal emittance of 5.5 nm·rad with insertion devices deactivated) an extremely fine tuning of the skew quadrupole correctors is required to find a possible improvement. The number of correction variables is large enough to argue the application of RWO. The target function is the measured vertical beam size.

RWO achieved a beam size of ~3.6 µm, corresponding to a vertical emittance of 0.9 pm·rad (with the contribution of spurious dispersion not subtracted) by optimizing the non-dispersive skew quadrupole settings (correcting betatron coupling). The beam size during the optimization is shown in Fig. 2.

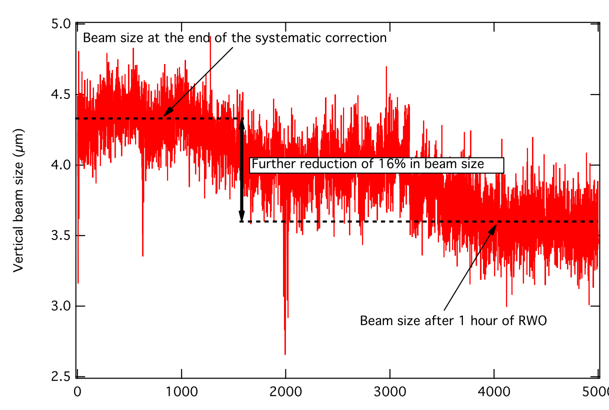

Figure 2: Vertical beam size during RWO.

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The reasonable step size of RWO was determined from the continuation of model-based correction, where the correction values fluctuated due to measurement errors. This corresponded to an rms correction current of ~10 mA for the 24 non-dispersive skew quadrupoles. We examined the step size in a range of 5~20 mA rms. The evolution of corrector settings during RWO are shown in Fig. 3.

At the end of RWO, it turned out that the model-based coupling correction was not fully limited by measurement errors since the change in the skew quadrupole settings reached ~70 mA rms, which was significantly larger than the step size chosen.

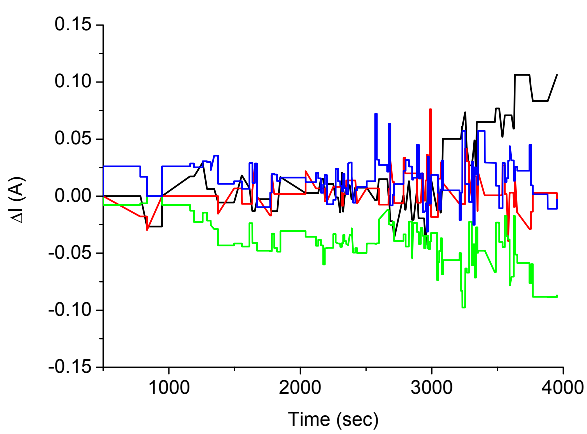

Figure 3: Evolution of non-dispersive skew corrector settings during RWO. The setting of four out of 24 correctors is shown, including unsuccessful steps that were removed before the next step.

Since we reached a beam size at the resolution limit of the existing beam size monitor, it remained inconclusive whether the dispersive skew quadrupole correctors were fully optimized or not.

The entire procedure of vertical emittance minimization is found in [7].

The RWO procedure can be easily automated for an on-line optimization. An automatic control of vertical beam size using 24 non-dispersive skew quadrupole was demonstrated as shown in Fig. 4.

CONCLUSION

We investigated the application of the RWO technique to overcome the limitations in model-based corrections, and it was indeed able to further improve the machine performance. There may be many useful applications, where a suitable target function is available. RWO has also great potential for use as on-line optimization tools.

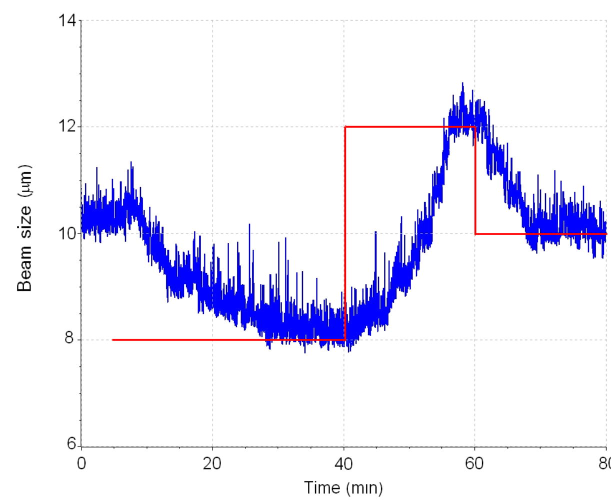

Figure 4: Automatic beam size control with RWO. The blue line shows the measured beam size. The initial beam size was ~10 μm. The target beam size was changed as shown by the red line and achieved by an automated RWO. The non-dispersive skew quadrupoles were used as knobs.

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