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FIRST ATTEMPTS AT APPLYING MACHINE LEARNING TO ALS STORAGE RING STABILIZATION*

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Abstract

The Advanced Light Source (ALS) storage ring operates multiple feedbacks and feed-forwards during user operations to ensure that various source properties such as beam position, beam angle, and beam size are maintained constant. Without these active corrections, strong perturbations of the electron beam would result from constantly varying insertion device (ID) gaps and phases. An important part of the ID gap/phase compensation requires recording feed-forward tables. While recording such tables takes a lot of time during dedicated machine shifts, the resulting compensation data is imperfect due to machine drift both during and after recording of the table. Since it is impractical to repeat recording feed-forward tables on a more frequent basis, we have decided to employ Machine Learning techniques to improve ID compensation in order to stabilize electron beam properties at the source points.

INTRODUCTION

To large extent the success of 3rd-generation light sources (3GLSs) such as the ALS lies in their stability, resulting in constant position, angle, and intensity of radiation delivered at a tunable wavelength with narrow width. In order to maintain constant intensity, a combination of top-off injection (maintaining constant beam current on a sub-percent level) [1,2] and precise control over source position and size is required. In 3GLSs source position and angle have been successfully stabilized through combined application of insertion device (ID) feed-forwards (FFs) and orbit feedback (FB) [3–5] resulting in sub-micron rms orbit stability over the course of many hours.

Source size stability, however, requires additional effort. Usually this calls for a local optics correction to compensate for perturbations caused by changes of ID settings (primarily focusing and skew quadrupole errors, but in some instances also higher-order corrections to maintain injection efficiency and lifetime) in combination with global optics corrections to ensure overall machine performance is maintained (tunes, betatron coupling) [4, 6–14]. Local optics corrections are commonly realized through a FF (local quadrupole and skew quadrupole FFs), while global corrections are often a combination of FF (e.g. systematic tune correction against ID motion) and FB (global tune correction).

Limitations of Feed-Forward Corrections

The FFs employed to correct systematic focusing and skew quadrupole errors resulting from ID motion are usually based on a physics model describing how e.g. the local vertical focusing is perturbed by a change of vertical gap along with measurements to determine which local quadrupole excitation is required to compensate for this effect. The result is commonly referred to as a *lookup table*. Such a lookup table is then employed by the local FF to compensate for ID motion. Two aspects about this approach are problematic: First, the physics model the approach is based on relies on several approximations (ideal IDs, linear expansion, linear superposition) which do not always hold well as experimental data shows. Secondly, the storage ring and the instrumentation involved in recording these lookup tables are susceptible to drift. This is a serious issue since recording lookup tables require large amounts of dedicated machine time so they can not be re-recorded on a frequent basis (1–2 recordings per EPU a year is the maximum that can realistically be expected at ALS). So as the machine drifts (e.g. temperature, ground settlement, tidal motion, etc.) during the period a table is being used, the fidelity of the FF compensation based on this table will reduce with time. However, even if tables were re-recorded more frequently, drift remains a fundamental problem since the machine instrumentation already drifts during the lengthy process to record the table[1].

SOURCE SIZE STABILITY

Standard practice in 3GLSs is to maintain transverse beam size stability to within 10% of the rms electron beam size [16, 17]. This performance is indeed routinely achieved at ALS and other 3GLSs despite machine drift and imperfections in the compensation for ID gap/phase changes. Now however, the latest experiments at these sources are starting to show limitations arising from such levels of source size control. While top-off injection and orbit FBs are routinely reaching sub-percent level stability, source sizes still vary on the level of several percent even in the most advanced 3GLSs after much optimization (cf. below for an example from a STXM end station at ALS) and thereby become the limitation for overall source stability.

It is also evident that with the advent of *4th-generation storage rings* (4GSRs)—sometimes referred to as *diffraction-limited storage rings*—delivering high-brightness x-ray beams with high coherent flux, electron beam sizes will become smaller by many more factors than perturbations

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[1] At ALS an EPU [15] requires on the order of one 8-hour machine shift to record a full lookup table.

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from IDs can be expected to reduce. In essence, if we do not find a way to improve how we compensate for foreseeable ID perturbations, the relative variations of source size will in fact become significantly larger than they are today thereby threatening the immense benefit of high coherent flux and brightness promised by these new sources. While first experiments at 3GLSs today are starting to hit up against the limit of source size stability, it is becoming clear that 4GSRs, operating at much smaller source sizes, will call for significantly tighter control over source size stability in order for experiments to exploit their ultra-high brightness and transverse coherence.

A typical example for the above mentioned source size stabilization challenge is shown in Fig. 1. Over the course

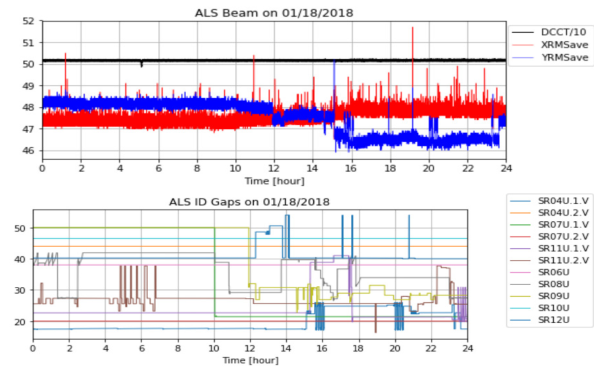

Figure 1: Electron beam size as measured the ALS diagnostic beamline 3.1 during a user run (top) showing roughly 2.5 μm variation (5%) in the vertical caused by changes in vertical ID gaps (shown, bottom) and horizontal EPU shifts (not shown here).

of 24 hours during regular ALS user operations with top off at 500 mA and all orbit FBs ad ID FFs operational, the vertical beam size as measured at diagnostic beamline 3.1[2] shows peak-to-peak variations on the order of 2.5 μm (5%). There are several discrete steps that exactly line up in time with changes in either vertical ID gaps (cf. Fig. 1 bottom) or horizontal phase changes in EPUs. Two main features can be observed: one is a fast step from one beam size to another concurrent with a change of vertical gap. The other consists of a repeated switching between one beam size and another in quick succession usually as a consequence of scanning horizontal phase back and forth in an EPU.

In both cases, the effect is seen primarily on the vertical beam size. This is related to the fact that upright quadrupole focusing errors are much better compensated for than skew quadrupolar errors. Gap and phase dependent local skew quadrupole contributions can perturb both betatron coupling and vertical dispersion wave. The primary effect of this, due to the very low emittance coupling, is a change in vertical emittance while the effect on horizontal emittance remains minute. In the vertical plane changes to the emittance are non-negligible and therefore result in clearly observed changes of vertical beam size.

In terms of vertical emittance, the ALS is a typical representative of 3GLSs. The machine is ideally flat and during machine setup for users, imperfections are corrected in order to remove betatron coupling and minimize spurious vertical dispersion through e.g. LOCO [18]. This, however, usually results in low Touschek lifetime since the vertical emittance is minimized. In fact, it can be suppressed far below the diffraction limit of most experiments in which case it offers only little benefit while presenting a significant lifetime penalty. In 3GLSs this issue is typically resolved by exciting a dispersion wave, where skew quadrupoles in the corrected lattice are excited in order to create limited amounts of vertical dispersion which then increases the beam size in the source points towards the diffraction limit thereby regaining lifetime without sacrificing brightness [9, 19–21]. It is clear, however, that any perturbation through skew quadrupole terms, such as those excited by a poorly shimmed ID, will perturb this delicate balance and can excite both betatron coupling and vertical dispersion.

Beamline Sensitivity to Source Size Stability

Certain beamlines are very sensitive to changes of the vertical beam size. Examples for this include beamlines that employ many slits to collimate the photon beam upstream of an intermediate focus or beamlines that disperse in the horizontal plane. In principle variations of intensity at the experiment can be dealt with by averaging or normalization. If an experiment, however, cannot independently measure the intensity on sample at any given time, normalization is not possible. Likewise, if an experiment only collects data during very brief periods of time so that averaging cannot be employed to reduce errors from step changes of source size, the experiment has to rely on a stable source.

An excellent example for an experiment in this situation is the STXM end station at ALS beamline 5.3.2.2 [22]. Figure 2 shows a scan performed at this beamline under standard user operations conditions. The intensity fluctuations seen as banding in the scan correspond to slow changes in source intensity driven by a varying vertical source size[3]. In such a scan the acquisition time per pixel is roughly 1 ms which is very fast compared to source size variations from ID changes. The latter can therefore not be averaged out. Because a typical experiment consists of comparing one such scan at one energy from another of the identical sample taken at another energy, such banding limits the experimental resolution. The noise floor of this STXM end station is roughly on the level of 0.5% rms dominated by vibrations in the beamline. The above example shows fluctuations more than a factor 6 beyond that.

[2] This beamline has excellent vertical resolution since the source point is located in the first arc dipole where $\beta_y \approx 100 \times \beta_x$ thereby generating a round beam despite low emittance coupling $\varepsilon_y / \varepsilon_x \approx 1\%$.

[3] The much smaller dark streaks observed in the scan are the result of stored beam perturbation during top-off injection. Since this is a very short and weak perturbation, this does not significantly impact typical STXM experiments, unlike the banding from strong low-frequency variations of sourse size.

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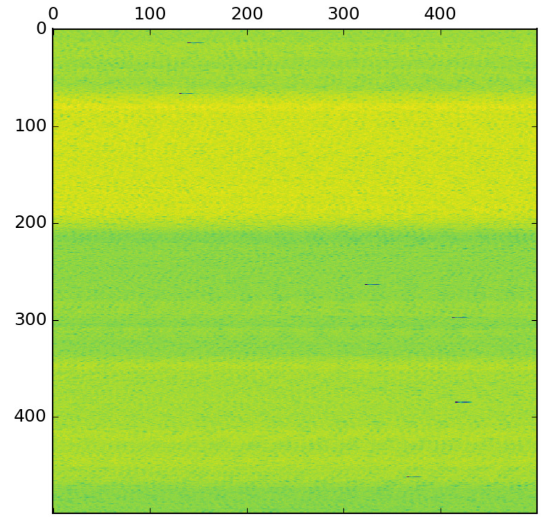

Figure 2: STXM image (500×500 pixels) from ALS beamline 5.3.2.2 at 390 eV showing banding (3.2% rms intensity variation) as a consequence of various ID configuration changes over the course of the scan (≈ 5 min acquisition time per scan).

MACHINE LEARNING APPROACH

Machine Learning (ML) has the potential to stabilize the vertical source points in ALS and thereby overcome beamline intensity fluctuations such as those described above. Requirements for ML are reproducibility and large data sets, both readily provided by the ALS. A significant benefit of ML is that it does not require a priori physics knowledge, but in turn allows extracting physics properties from a trained model a posteriori. Since source size control in the ALS is already based on a physics model (which experiments have proven to be incomplete), the prospect that ML allows enhancing and improving such a model is highly attractive.

Machine Learning in this application requires training a neural network (NN) to make predictions for resulting beam size in ALS as a function of all ID settings as well as all skew quadrupole excitations since these are the two sets of parameters we claim are responsible for source size variations around the storage ring. Once we are successful in training such a NN, we are armed with a prediction for beam sizes at any given time. This prediction can then be used to adjust the skew quadrupoles in a FF manner to compensate for the anticipated beam size variation thereby stabilizing the beam size in most source points at ALS.

We have spent much time optimizing a NN for the ALS situation. Details will be presented in a separate publication [23]. Data acquisition initially took place during dedicated physics shifts where we actuated ID gaps and phases repeatedly in an attempt to mimic user operations. During acquisition we logged all ID parameters as well as stored current, beam sizes (as measured at diagnostic beamline 3.1), skew quadrupole settings, and a few other machine parameters at 10 Hz. We have been successful in training a NN to make accurate predictions of the beam size as we scan almost all of our IDs through their entire operational parameter space. An example for such a prediction is shown in Fig. 3. Equipped with this prediction we can then proceed

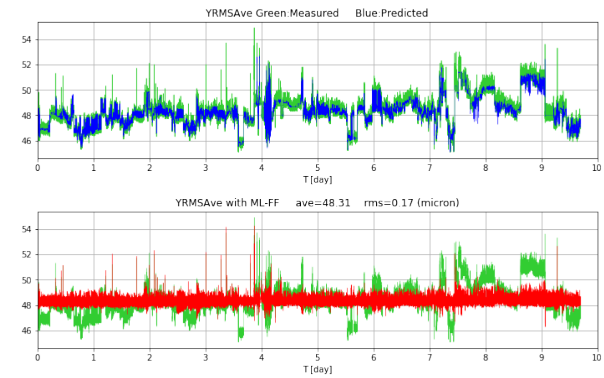

Figure 3: Beam size prediction by the trained NN. Top: Measured beam size (green) vs. NN prediction (blue). Bottom: simulation of NN-based correction with measured beam size (green) vs. prediction subtracted from measured beam size (red). This residual is on the sub-percent rms level.

to use the NN as a FF to stabilize beam size. At every step (the NN-based FF currently runs at ≈ 2 Hz) the trained NN is queried for expected beam sizes as a function of many possible skew quadrupole excitations. The FF checks which one of these configurations is predicted to render a vertical beam size matching our vertical beam size target and then downloads that configuration to the skew quadrupole power supplies.

First trials during machine physics shifts using a subset of IDs indicated that the NN-based FF was able to stabilize the vertical beam size in ALS to the sub-percent rms level. Of course the crucial benchmark here is not the measured stability at the diagnostic beamline, but rather at the most sensitive source points. We therefore again analyzed STXM scans taken at 5.3.2.2, this time while the NN-based FF was running and IDs were being scanned. The rms intensity noise in the STXM scan was reduced to 0.6% rms, a more than factor 5 improvement compared to no NN-based FF (cf. Fig. 2) and only 50% above the absolute noise floor of the STXM end station.

OUTLOOK

Equipped with encouraging results from our first trials during machine shifts we have started running this NN-based FF during user operations. We confirm a stabilization of vertical source size in ALS to the sub-percent rms level over the course of a typical user run. Operating the NN-based FF during user operations allows us to collect much more training data which we expect to use for online retraining of the NN in the future. This should allow better correction, reducing the amount of machine time required for initial training, and more importantly, updating the NN to follow a drifting machine as well as changes in ID configurations commonly applied by users.

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