PARTICLE SWARM OPTIMIZATION ALGORITHM APPLIED IN ONLINE COMMISSIONING AT THE MLS AND BESSY II

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Abstract

Particle Swarm Optimization (PSO) is a population based optimization technique inspired by the social behaviour of bird flocking [1]. This algorithm has been successfully used for beam dynamics simulations due to its excellent capability to deal with large-dimensional optimization problems [2, 3]. At the MLS and BESSY II PSO was first successfully applied to improve the lifetime by 20 ~ 30% within only 10 iterations respectively. Now the PSO has been implemented as a multifunctional online optimizer to improve the machine performance. This paper presents some results of online experiments.

INTRODUCTION

The Metrology Light Source (MLS) is a electron storage ring operated at the energy of 105 ~ 630 MeV for metrology applications in the THz to extreme UV spectral range [4], while BESSY II is a top-up synchrotron light source operated at 1.7 GeV [5]. Nonlinear dynamics optimizations are continuous ongoing work for MLS and BESSY II. Nonlinear dynamics affects beam lifetime and injection efficiency. Beam dynamics simulations provide the preliminary settings of the machines, however, the real machines deviate from the models in simulations unless the models are good enough. Therefore online optimization is a suitable tool to improve machine performance.

A global scan method with chromaticity constraints has been used to adjust the four families of sextupoles at the MLS to improve the lifetime [6]. However it is difficult to use this method to optimize ten harmonic sextupole families at BESSY II simultaneously, because it would take months to finish a coarse global scan. A practical and fast method should be introduced.

Particle Swarm Optimization (PSO) algorithm has already been used in beam dynamics optimization in simulations for years [2,3]. It is considered to be a promising method to optimize harmonic sextupoles setting at BESSY II, and was first tested at the MLS for online lifetime optimization. Then PSO has been used at BESSY II for lifetime and injection efficiency improvement. The algorithm shows its advantage of fast convergence, especially in large-dimensional cases. Now PSO optimizer based on *pyswarm* package [11] has become a standard tool for machine commissioning.

PSO ALGORITHM

Particle Swarm Optimization (PSO) was developed by Dr. Kennedy and Dr. Eberhart in 1995 [1]. PSO is inspired by the following scenario: A group of birds are randomly distributed in certain space searching the only single piece of food. No bird knows where the food is. But the bird nearest to the food automatically becomes the leading bird and directs the flight. The leading bird and the position of all birds update until the food is found. In computer science PSO is implemented as a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to given measure of quality, and this quality is named as "fitness value". It solves a problem by having a population of candidate solutions, dubbed "particles", and moving these "particles" around in the search space according to simple formulas [7].

Taking the beam lifetime optimization by adjusting N sextupoles as an example, better lifetime is expected to be achieved with enlarged dynamic aperture. The swarm is initialized with M random sextupole settings. Each setting is considered as the position of a particle, containing the strength of N sextupoles. The beam lifetime with each setting as the fitness value is measured respectively in every iteration, and the settings are renewed iteratively by following two best values. The first one is the best lifetime the swarm has achieved so far and the setting is named as "global best" (gbest). Another best value tracked by PSO is the best lifetime every individual particle has experienced, namely each particle has memory and remembers its best setting as "personal best" (pbest). Since one sextupole setting can be regarded as a coordinate in the N-dimensional space, an N-dimensional vector, referred to as the "velocity" in PSO, is introduced here to determine how the sextupole settings change from one iteration to the next. The formulas are described in Eq. 1 and Eq. 2 [7].

$$x(k+1) = x(k) + v(k+1) \qquad (1)$$

$$v(k+1) = w*v(k) + c_1*rand()*(pbest - x(k)) \\ + c_2*rand()*(gbest - x(k)) \qquad (2)$$

where the v(k),v(k+1),x(k+1) and x(k) are the velocities and positions of a particle in k^{th} and $(k+1)^{th}$ iteration, w, c_1 and c_2 denote the inertia factor, cognitive factor and social learning factor, which are the weights of present motion, particle memory and the swarm influence in determining the velocity. Proper weights should be chosen to cover fast convergence and global search ability [8].

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ONLINE OPTIMIZATION RESULTS

Lifetime Optimization at the MLS

Four independent sextupole families are used to correct the chromaticities and adjust the dynamic aperture at the MLS, so chromaticity constraints are needed to make sure the results will not be affected by instabilities, like head-tail instability. Hence zero lifetime as penalty is assigned to the settings which lead chromaticities smaller than 0.1 horizontally or vertically. The PSO method was tested for the newly developed low-emittance optics and compared with global scan. Different combinations of current values of 4 independent power supplies are generated in a preset range as the initial condition, and the settings are varying iteratively within the range until the algorithm converges or maximum iterations are reached.

The optimization starts from the standard sextupole setting at that time, and the corresponding normalized lifetime is set to 1. Fig. 1 shows significant improvement has already been reached in the first iteration and the improvement is saturated after 6 iterations, and the optimization last 0.5 h. Three different PSO runs are compared with global scan in Fig. 2. It shows that optimized results with PSO achieved within 6-15 iterations are close to global optima, although they are not unique. It also means PSO cannot guarantee that global optima will be found, but significant improvement is rapidly achievable. The discrepancy between global optima and optimum value obtained from PSO can be reduced with more iterations, however, it is limited by the experimental time. Nevertheless, absolute optima is not necessary in the machine commissioning since the PSO optimized result is close enough to the global optima.
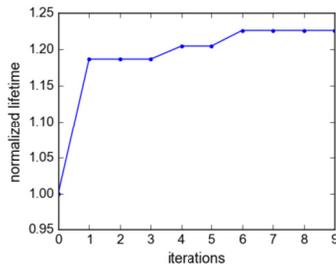
Figure 1: History of best-to-date solutions during the lifetime optimization with PSO at the MLS.

Lifetime Optimization at BESSY II

The sextupole setting of BESSY II was determined by a global scan of 4 families of harmonic sextupoles, S3D, S3T, S4D and S4T, and it was not systematically optimized after the modifications of the machine optics for the EMIL project which makes the number of independent sextupole circuits increased to 10 [8, 9]. Thus the lifetime was not at optimum due to reduced dynamic aperture. Global scan method is not a practical way to optimize the dynamics aperture if 10 harmonic sextupole families are to be optimized simultaneously, therefore the PSO was tested to improve the lifetime. In order to emphasize the impact of Toushek effect, 10 high-current bunches homogeneously filled in the storage ring were

used to measure the lifetime when the overall current decreases from 50 mA to 40 mA. The injection efficiency is used as a constraint to filter those sextupole settings which lead the injection efficiency less than 90%. The optimization starts with the standard sextupole setting for daily operation. The lifetime can be improved by ~30% after 9 iterations, which means 315 different sextupole combinations tried in the optimizations. The results are shown in Fig. 3.
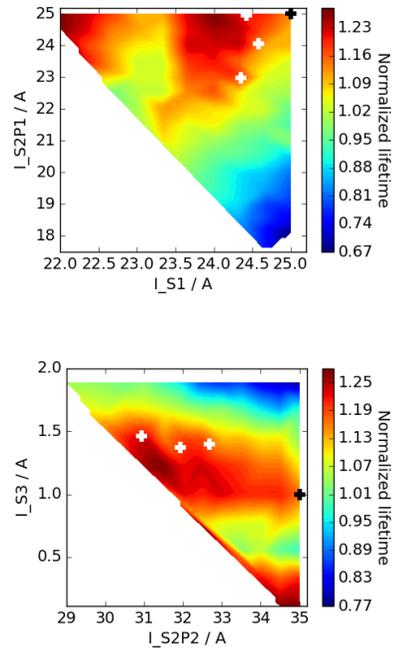
Figure 2: Comparison of three PSO runs with 4D global scan projected on S2P1/S1 plane (top) and S3/S2P2 plane (bottom). The black crosses mark the standard setting whereas the white ones the PSO optimized setting, and the global optima is denoted with darkest color in the contour map.
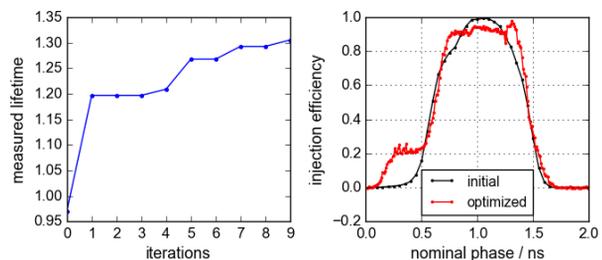
Figure 3: History of best-to-date solutions during the lifetime optimization with PSO (left) and phase acceptance measurement (right) at BESSY II.

Scanning the 500 MHz RF phase between the booster and the storage ring with regard to injection efficiency was performed to verify the optimized sextupole setting, which is called phase scan here. Off-phase injected electrons are equivalent to off-momentum ones, therefore the result of phase scan can be taken as a measure of dynamic apertures at different momentums. It is shown in Fig. 3 that the new sextupole setting leads to larger phase acceptance, which can be described as the width of the

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phase scan curve. Especially, the injection efficiency has been noticeably improved in the off-phase (0.1 ~ 0.5 ns) part.

Phase Acceptance Optimization at BESSY II

Lifetime optimization is not the most efficient way to improve the nonlinear performance, because the lifetime measurement takes long time. Moreover, beam size fluctuations due to emittance coupling change caused by new sextupole setting and spin polarization also affect the lifetime [10].

A simplified way of phase acceptance optimization is to use injection efficiency at off-phase area as the fitness value in order to broaden the plateau part of the phase scan curve. A PSO run based on manually optimized sextupole setting is given to illustrate the method. The nominal phase between booster and storage ring is set to 0.36 ns, marked with green line in Fig. 4, while it is set to 1 ns in standard user operation. A better solution has been found after 12 iterations. The phase scan shows a broader plateau, whereas the average injection efficiency of this area is slightly smaller, which can be improved by adjusting the pulsed injection elements.
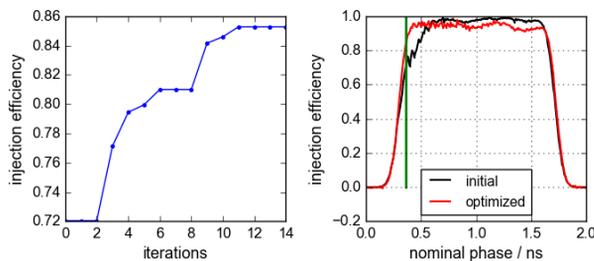
Figure 4: History of best-to-date solutions during the injection efficiency optimization with PSO (left) and comparison of phase acceptances with initial and optimized sextupole setting (right) at BESSY II.

A better way is to use the sum of one on-phase injection efficiency and two off-phase ones to represent the phase acceptance. An example to optimize the injection efficiency against strong nonlinear effect caused by certain insertion devices is given. The on-phase setting is 1 ns, and the other two are 0.35 ns and 0.7 ns, which are marked with green lines in Fig. 5. The black curve denotes the reduced phase acceptance compared to the situation with open insertion devices in Fig. 4. After 9 iterations, a reasonable good setting was found, and the phase acceptance has been dramatically enlarged, marked in red.

CONCLUSION AND OUTLOOK

The PSO algorithm has proved to be a useful online optimizer to for the nonlinear dynamics at the MLS and BESSY II.

As a population based algorithm, the PSO cannot guarantee global optima in every optimization run, however the significant improvement can be achieved quite fast. Besides, the PSO algorithm itself is not robust against noise, so proper measures should be taken to reduce the noise of the fitness value. The approach used at BESSY II and MLS is deleting the maximum and minimum measured values and averaging the rest, and it is verified that this method works well, although at the price of longer optimization time. The algorithm should be consummated with better robustness, thus the measurement time of fitness values can be reduced and the PSO can work more effectively with more iterations.
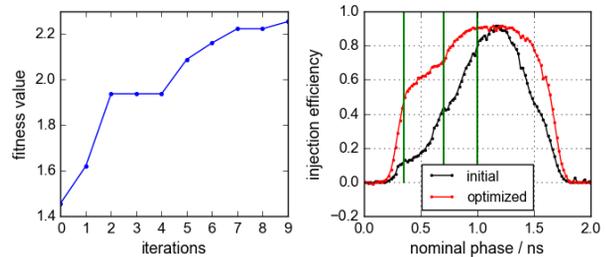
Figure 5: History of best-to-date solutions during the phase acceptance optimization against strong IDs with PSO (left) and comparison of phase acceptances with initial and optimized sextupole setting (right) at BESSY II.

The investigations to extend the optimizer to more aspects are going on in both machines. To reduce the vertical coupling at BESSY II by tuning the skews and to increase the injection rate by adjusting elements in the transfer line at the MLS are on the schedule.

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