ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPGW010

FIRST APPLICATION OF ONLINE PARTICLE SWARM OPTIMISATION AT SOLEIL

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Abstract

First attempts of online optimisation of SOLEIL using Particle Swarm Optimisation (PSO) is reported with two major applications. This technique proves to be particularly suitable in a control room and could become a standard operation tool for tuning the accelerators in complement of other techniques. The first optimisation of the injection in the storage ring will be presented using the injection septa and the vertical correctors of the booster to storage ring transfer line. The second work will summarise the results obtained from the optimisation of the transverse on- and off-momentum dynamics in presence of insertion devices. Main results, the implementation and improvements will be presented and discussed thoroughly.

INTRODUCTION

SOLEIL is the French third generation synchrotron light source operating since 2007 with a 4 nm.rad emittance at an energy of 2.75 GeV [1, 2]. It has been delivering extremely stable photon beams of high average brightness to 29 beamlines using photon energies in a range of ten orders of magnitude from the IR/UV/VUV up to hard X-rays. In daily operation, 27 diverse insertion devices (IDs) are freely controlled (gap/phase) by the users with the exception of an out-of-vacuum wiggler (W164) and an in-vacuum wiggler (WSV50) operating at fixed gaps. The storage ring (SR), whose main parameters are given in Table 1, hosts 2 in-vacuum Cryogenic Permanent Magnet Undulators (CPMUs), 6 In-Vacuum Undulators (IVUs), 13 Apple-II type undulators, and 4 electromagnetic IDs in addition to the two wigglers. The injector complex is made of a 110 MeV linac and a full energy booster. The beam is injected into the horizontal plane; all injection elements are installed in a single 12 m long straight section: 4 fast kickers, a Eddy current septum and a thick septum [3].

Table 1: Storage Ring Main Parameters

Parameters	**Values**
Energy [GeV]	2.75
Circumference [m]	354.097
Symmetry	1
Natural Emittance [nm.rad]	4.0
Tunes (H/V)	18.155/10.229
Natural Chromaticities (H/V)	−53/−19
Lifetime @ 500 mA, 1% coupl.	15 h
Injection Efficiency w/ IDs	70-80 %

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MOTIVATION

Automatic beam-based optimisation is complementary to other tools available [4] to tune the performance of an accelerator. One of the motivations of this work is to shorten the tuning time to optimise the injection efficiency into the storage ring. Today the injector operation performance may vary for several reasons: thermal drifts of the injector after a shutdown period, variation of the efficiency of injection pulsed magnet related to an unexpected control malfunctioning or timing or equipment drifts. Up to now the operator on shift takes notice of the performance degradation and looks for solution to recover the situation: typically, the first attempt is to *manually* retune the injection using the two SR injection septa and the two final vertical correctors of the booster-to-storage ring transfer line. The steering of the beam in horizontal and vertical plane is done blindly and can take a significant time. The goal is then to reduce this time by using a PSO-based algorithm in a first step, which could be completed in a second stage by using machine learning capabilities.

As a second application, PSO is used to optimise simultaneously the lifetime and the injection efficiency of the storage ring by scanning experimentally the sextupole magnet settings. The lifetime and the injection efficiency are proxies for the dynamic aperture (DA) and the longitudinal momentum acceptance (LMA). If the bare lattice is very well characterised and in full agreement with the simulation [5, 6], the challenge is to find a robust working point with respect to the insertion device configurations. As explained in the introduction, the ID parameter space may be very large; its dimension is 48 if all the gaps and phases of mechanical IDs and main currents of electromagnetic devices are taken into account. Even if each single ID has been individually tuned and has local feedforward corrections or passive corrections (magic finger, etc.) when required, the residual defaults and the ID transverse field roll-off may still impact the performance through nonlinear cross talks. This is enhanced furthermore by the fact the lattice has lost over the years part of its immunity to ID configurations especially after operating the accelerator in a 1-fold symmetry (instead of the design 4 fold-symmetry) for accommodating two canted in-vacuum CPMUs [7–9] and pushing further down the vertical betatron function to allow operation of the in-vacuum wiggler at 4.5 mm minimum gap. Unfortunately it is not possible to get a precise modelling of each single ID, especially for a few of them which strongly impact the beam dynamics [10] (10 m long 640 mm of period HU640, nonlinear cross talk of in-vacuum IDs due to the B-field roll-off related to their limited pole widths, etc.). At the end,

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the final optimisation of the storage ring fully loaded with IDs has to be done online using the beam directly to probe of nonlinear beam dynamics of the electron beam and has become a time-consuming process.

This work will also be very much beneficial for the forthcoming modifications of the storage ring (breaking the symmetry even furthermore by replacing in the coming year a 1.71 T dipole with a 2.8 T superbend, installing a multipole injection kicker with a reduced vertical aperture, etc). Finally PSO-like tools may become relevant with the expected SOLEIL major upgrade to a 4th generation synchrotron light source with a natural emittance lower than 100 pm.rad [11].

METHODOLOGY

Following the work presented in Ref. [12], Particle Swarm Optimisation (PSO) was chosen for evaluation as an online tuning tool. PSO is a computational method developed in 1995 by Kennedy, Eberhart and Shi [13–15] and was first intended for simulating social behaviour as a way to represent the movement of organisms such as bird flocks or fish schools. The readers are directed to Ref. [16] for a comprehensive survey and technical presentation of PSO and its applications.

A set of particles (p) is called a swarm. The particle swarm size D and the convergence of the algorithm may significantly depend on the problem to solve. Several studies have been carried out to define the best suitable swarm size and characterise the convergence speed. This is still a open topic; M. Clerc suggests [17] to take $10 + 2[\sqrt{D}]$ as swarm size where D is the dimension of the parameter space and [] is the integer part operator. After a random initialisation of the swarm, a fitness function is evaluated to compare and classify the particles. A local optimum solution ($pbest$) related to a particle and global optimum are then defined ($gbest$). Then the process is iterative: the coordinates of each particle follows an evolution law made of a inertia term (w) balancing the global exploration and the local exploitation and two acceleration coefficients, namely a cognitive component c_1 to find the local optimum solution and a cooperation component c_2 to find the global optimum solution. A step $k + 1$, new coordinates are given by:

$$p(k+1) = p(k) + v(k+1)$$

where the velocity $v(k + 1)$ is defined by

$$v(k+1) = w*v(k)+c_1*r_1*(pbest-p(k))+c_2*r_2*(gbest-p(k))$$

and r_1 and r_2 are two random numbers uniformly distributed within the range [0, 1], $w = 0.72984$ and $c_1 = c_2 = 1.49618$.

The code originally developed for Bessy-II in Python langage was modified to be integrated in the TANGO control system.

MAIN RESULTS

Injection Optimisation

In this experiment PSO is used to improve the injection efficiency into the storage ring. To reduce the beam losses during the optimisation process, a 0.3 nC low charge 104 bunch train is used. The stored beam current is maintained below 10 mA to avoid any collective effect to allow fair comparison of the performance between all the particles. The injection is averaged 3 times filtering out any spoiled measurement. The Eddy current septum, thick septum voltages and the currents of the last two correctors namely CV4 and CV5 of the transfer line from the booster to the storage ring are varied within the limits given by the Table 2.

Table 2: Variation Range of the Injection Parameters used for the PSO Optimisation

Parameters	HW Values	Physics Values
Eddy curr. septum	[530, 550] V	[279, 289] mrad
Thick septum	[90, 93] V	[102, 105] mrad
CV4 corrector	[−6, −4] A	[−0.73, −0.48] mrad
CV5 corrector	[0, 8] A	[0.00, 0.97] mrad

Figure 1 shows the results of two PSO experiments covering the parameter space using a swarm size of 14. In red are highlighted all the results with larger injection efficiency than 85 %. Each particle evaluation takes 30 s, which is mainly related by the time to get the information from the control to measure the injection rate.The injection performance was improved from 85 % up to 99 %.

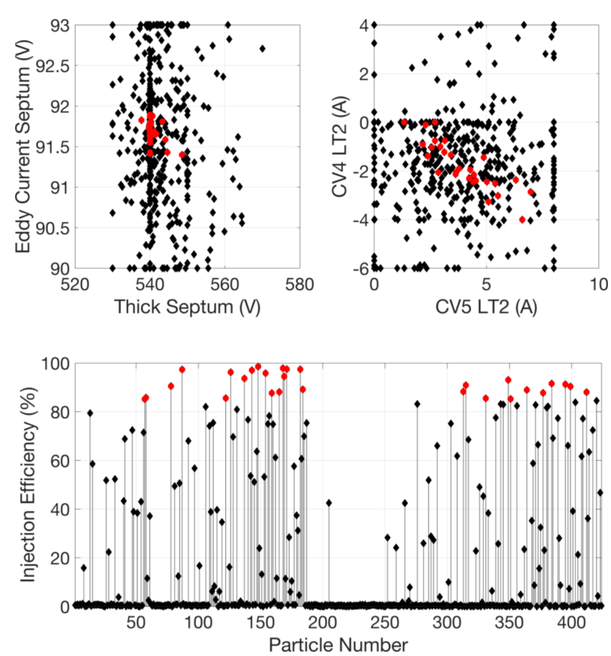

Figure 1: Lower graph: Evolution of the injection rate along the particle PSO iterations. Upper left: Settings of the Eddy current septum and thick septum. Upper right: Settings of the two vertical correctors.

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Storage RING Performance Optimisation

In this experiment, PSO is tested to improve the global beam performance for a storage ring lattice fully loaded with IDs, which is a fair representation of the ring performance during user operation.

A rapid and efficient way to probe both the on-momentum and off-momentum transverse beam dynamics consists in measuring the injection efficiency with respect to the RF phase shift between the booster and the storage rings. The phase was measured by using a direct non-IQ demodulation technique integrated in the TANGO control system [18] developed specially for this experiment. This method reveals to be much more faster than estimating the Touschek lifetime.

Figure 2 shows in blue colour this figure of merit for the so-called bare lattice corresponding to a symmetrised lattice (beta-beat below 1 % RMS) with all IDs open or switched-off except the two wigglers closed to operation fixed gap values. The injection efficiency curve has a plateau of 4 % with a rate of nearly 80 %; leading to a fairly large energy acceptance. As soon as the other IDs are set into operation, the performance drops dramatically (red curve): on momentum injection rate reduced by 15 % and narrower momentum acceptance.This behaviour was reported earlier using frequency map analysis [10].

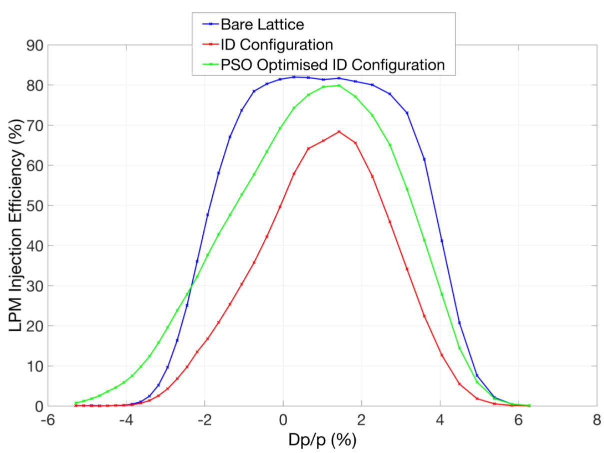

Figure 2: Injection efficiency along the RF phase shift between the booster and the storage rings converted in energy offset for 3 configurations using the modelled lattice in AT [19]. The performance drops dramatically between the bare lattice (in blue) and the addition of the IDs (in red). After applying 3 iterations of PSO, the performance are significantly improved (curve in green).

The PSO algorithm was employed in order to test whether the performance can be recovered by changing the sextupole configuration (11 families) while keeping the chromaticities locked to the operation values. In this experiment the proxies used for estimating the size of the dynamic aperture are the injection efficiency for an energy offset of -2, 0, and 2 %. The parameters used for the experiments are given in Table 3.

Table 3: PSO Parameters for the Storage Ring Optimisation

Parameters	**Values**
Maximum current	10 mA
Chromaticities (ξ_x, ξ_z)	(0.8-1.7, 1.5-2.5)
RF-voltage	2.6 MV

The swarm size is chosen to be 40 and the sextupole setting values are allowed to vary in the range ±50 A from their nominal values. The evaluation time for each particle lasts 90 s. The preliminary results show after only 3 iterations encouraging results with a improvement by 15 % for the injection efficiency for on-momentum particles. The momentum acceptance is also enlarged by ±1 %. It is worth noting that for the best solution several sextupole family currents have large offset up to 20 and even 30 %, values which were unexpected and not tested manually intuitively by an operator in the control room (Table 4).

Table 4: Sextupole Setting Variations

Param.	**Start (A)**	**Best (A)**	**Δ (A)**	**Var. (%)**
S1	90.06	81.68	8.37	-9.30
S2	-192.78	-155.19	35.59	-19.50
S3	-98.6	-129.72	31.11	**31.56**
S4	205.6	241.28	35.68	17.35
S5	-210.83	-223.19	12.36	5.86
S6	196.62	178.12	18.5	-9.41
S7	-294.95	-309.26	14.3	4.85
S8	229.91	259.65	29.73	12.94
S9	-237.07	-210.02	27.04	-11.41
S10	137.4	110.82	26.58	-19.34
S11	70.06	83.22	13.16	18.78

CONCLUSION & PERSPECTIVES

The first application of PSO for tuning the linear and nonlinear parameters have shown promising results. For future plans, we aim to reduce significantly the time measurement which is largely dominated by the acquisition time to get the injection efficiency. The goal is to install a timing board to make injection efficiency measurement available at 3 Hz rate time-stamping and synchronising the data of the DCCTs of the storage ring and booster ring. The algorithm will be ported in Matlab for becoming a standard operation tool.

ACKNOWLEDGEMENTS

The two first authors are thankful to the operation group for their support and the accelerator physics group for useful discussions and suggestions. The RF-group is thanked for providing a board to remotely control the RF phase via Non-IQ direct demodulation of the phase. K. Manukyan (from SESAME light source) contributed to the first measurement and the commissioning and the calibration of the dedicated board.

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