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LATTICE STUDIES OF A BOOSTER SYNCHROTRON FOR PETRA IV

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Abstract

Associated with an upgrade study of the PETRA III light source toward ultra low-emittance is an upgrade study of the booster synchrotron. One possible solution obtained from a scaling of the ALBA booster to a circumference of 300 m is considered. It is based on a modified FODO lattice with combined function magnets and achromat straights. In this paper a method utilizing piecewise matchings supervised and optimized with evolutionary algorithm (PMSOEA) was devised to search the lattice. Some preliminary results are shown and discussed.

INTRODUCTION

The current injector DESY II needs an upgrade. The new injector aims at the emittance less than 10 nm-rad. ALBA's booster features the combined function FODO cells and the dispersion suppressor [1]. Figure 1 depicts an example of this type of lattice and the magnet naming convention [2]. The sextupole components of the combined function magnets BD and QF correct the chromaticity. The dispersion suppressor is composed of a smaller dipole BM and a quadrupole QM in a proper location. Two extra families of sextupoles are installed to compensate the chromaticity shift induced by the eddy current during the ramping. TPS's booster also adopts this design [3]. The advantage of this type of lattice is the simple structure with the sufficient small emittance provided.

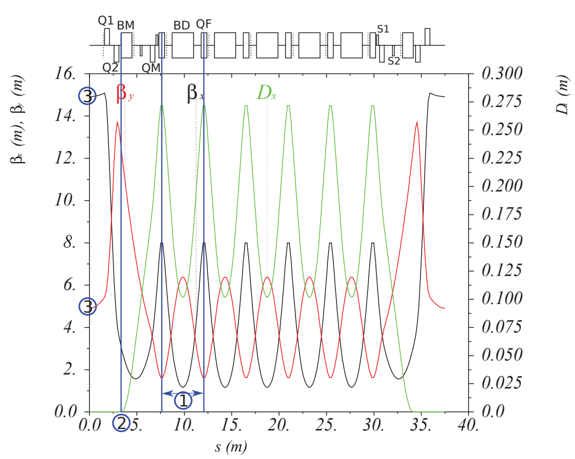

Figure 1: Lattice schematic and the naming convention.

In 2016, Dr. Dieter Einfeld composed a 3-fold symmetry design by scaling ALBA's booster to 300 m [4]. Nevertheless, it has to be reshaped to 8-fold symmetry to fit the inner walls in the existing tunnel in DESY II.

Since the basic structure is determined, the next step is to find a stable solution to start with. It is not always easy to do so by blindly random guessing. A better way is to construct the lattice by piecewise matchings of smaller pieces. To build this type of lattice, there are four matching steps. The matching steps are described as follows. The related checking points are indicated in Fig. 1.

1. Find a periodic solution of the FODO cells with the phase advances as the tuning knobs.
2. Take the optics from the previous step and propagate the optics through the dispersion suppressor. The achromat condition has to be matched.
3. Propagate the optics from the previous step so that it is symmetric in the straight section center. The periodical solution is done by the quadrupole doublet.
4. The chromaticities are adjusted by the sextupole components built-in in combined function magnets.

A method utilizing piecewise matchings supervised and optimized with evolutionary algorithm is therefore devised to guide these steps. This algorithm performs two-level manipulations. It firstly supervises the optics matchings and then optimizes the objectives per requests. The lattice construction and the technology/physical constraints are integrated in this algorithm. The details are explained in the following section.

PMSOEA

Motivation and Idea

A typical way to get some sense of the properties of a high dimensional problem is to probe the topology iteratively. The above matching procedures have to be repeatedly performed. During the iterations, the lattice parameters and the matching parameters are tweaked accordingly until satisfactory solutions are found. Usually these matchings are checked manually and need heavy operations which are time-consuming. Also, the tuning are supervised by very experienced human judgements which sometimes could be wrong. All these operations and human brain works can be systematically automated by the machine.

A guided random search is proved more efficient than blindly random search such as the Monte Carlo method. Therefore a more efficient systematic search by the stochastic evolutionary search algorithm with multiple objective optimizer was proposed [5]. It was dedicated to optimize the H7BA lattice in terms of the emittance versus the straight section length. For a multiple objectives optimization problem, usually the objectives are the quantities which can not be optimized simultaneously. The purpose is to find a set of optimal solutions in the objective space so that any good decision lays on it. This optimal set is called the pareto front.

In addition to the objectives, the dominance constraints [6] defining the feasibility of the individuals are introduced to improve this method. The pareto front is searched only

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among the feasible solutions. Here the dominance constraints are mainly used for the supervision of the lattice construction. So the matching penalties are part of the constraints and the matching parameters such as the optics can be included in the variables.

A good evolutionary algorithm must take care both the good efficiency of the convergence and the divergence of the population. The ultimate goal is to find satisfactory solutions with limited computing power in a reasonable time duration.

The Implementation

The evolutionary algorithm used here is based on the framework developed by PISALib [7]. The algorithm is handled by two separate programs named the variator and selector. The variator is responsible for breeding and evaluating the offsprings, while the selector sorts and selects the population for the next iteration according to their fitness functions. The sorting algorithm employed here is SPEA2 [8]. The information shared and exchanged between the variator and selector is carried out by file I/O in the operating system.

Some tricks and assumptions are made to simplify the process. The angle variables can be manipulated but for simplification we fix all the angles. We assume 5 FODO cells in each superperiod and the angle of the bending magnet in each FODO cell is 7.5°. The bending magnet in the dispersion suppressor is assumed a pure dipole with the angle 3.75°. The 4 matching steps are carried out by the Nelder-Mead simplex method in NLOPT [9]. The boundaries of these matching variables are given according to the engineering capabilities. The lengths of elements and drifts are round to mini-meter scale.

The variables There are 14 variables which include the lattice and matching parameters. Eleven of them are the lengths of elements and the space between them. Two are phase advances for the FODO cell, and the last one is the slope of vertical beta function in the end of the dispersion suppressor. The lower and upper boundaries should be reasonably given. The straight section length variable is sacrificed and moved to the constraints in order to preserve the total circumference. All the rest lattice parameters are determined via the matching process.

The dominance constraints Here the matching penalties, engineering limits, and other constraints are added in the dominance constraints to guide the lattice construction. A special attention is needed to be paid to avoid the pitfall when re-partitioning the damping coefficients with combined function magnets. In total, 7 dominance constraints are checked.

- Four of them are from the matching penalty functions. The matching is claimed good only if its penalty is less than the corresponding tolerance.
- The damping partition ($\mathcal{D}$) is within $(-2, 1)$.
- The straight section length (L_1) is long enough to accommodate the RF modules (larger than 3 meter).
- An upper limit of the natural emittance (ε_0).

Negative values of dominance constraints represent the infeasibility. The selection mechanism of the algorithm will automatically drop the infeasible solutions and converge all population to the feasible ones. A proper design of the dominance constraints can help the convergence.

The objectives The objectives must to be properly chosen and designed. To have good single particle dynamics properties, the working tune should be away from dangerous resonances and the tune spread area in phase space should be as localized as possible. A naive choice of the objectives considers the nonlinear chromaticities to the third order ($C_{x2}, C_{z2}, C_{x3}, C_{z3}$) and the amplitude dependent tune shifts to the linear order (ADTS). The 4 terms regarding the second and third order nonlinear chromaticities in both planes are obtained from numerical fitting. The first objective is a scalar derived from the combination of these terms, with 10 times smaller weights on the third order terms. The second objective is the root of the sum of the 3 squared ADTS terms. Balancing the speed and the accuracy of numerical calculations, the adequate number of slices in a combined function magnet is chosen to be 10. The fitness functions are obtained by properly scaling the objective functions to the range [0, 1].

The evaluation After a new individual is bred, the algorithm has to check its feasibility. If all the dominance constraints are fulfilled, then a feasible lattice is constructed and the objectives can be evaluated. In practice, the following layered pseudo code shows the dissection of the evaluation process and the logic behind.

```
Perform match_1 and set constraint_1
if (constraint_1 is fulfilled)
  Perform match_2 and set constraint_2
  if (constraint_2 is fulfilled)
    Perform match_3 and set constraint_3
    if (constraint_3 is fulfilled)
      Calculate linear lattice properties
      Set constraint_4, 5, 6
      #(L_1 > L_min and -2 < D < 1 and ε_0 < ε_max)
      if (constraint_4, 5, 6 are fulfilled)
        Perform match_4 and set constraint_7
        if (constraint_7 is fulfilled)
          Evaluate (C_x2, C_z2, C_x3, C_z3) and ADTS
```

The matching step 3 and the estimation of ADTS are more computational expensive than others. If any of the dominance constraints is violated, the individual is considered infeasible and the estimation will abort. No objectives will be evaluated for the efficiency consideration.

RESULTS

As a benchmark, the elapsed time is 22 hours for 500 iterations with 100 offsprings in each new iteration. This is achieved by a single thread execution with a modern desktop

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CPU. The actual time consumed scales linearly with the size of the population and the number of iterations, and is inverse proportional to the number of parallel threads.

During the simulation, the whole population gradually become feasible after a few ten iterations. Figure 2 shows the improvement of the pareto front as the generation evolves, along with the final results from constraints with different emittance bounds. As the generation evolves, the population approach the emittance upper limit. In fact, the emittance can be set as the third objective if it is an important factor for decision making. In our case it is not necessary to be minimized so we stay with $\varepsilon_0 < 10$ nm-rad.

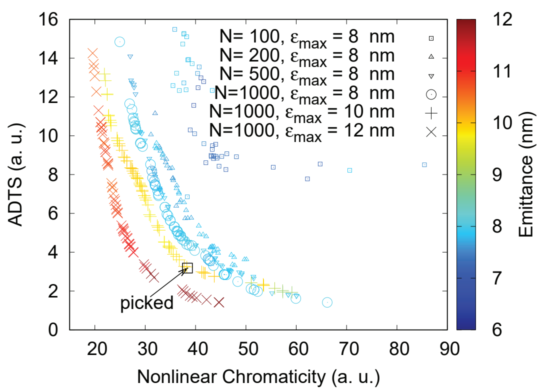

Figure 2: Pareto fronts evolution and the results with different emittance limits.

To choose good solutions, one has to check other properties such as the working point and beta functions, etc. A solution is picked for further investigations, as indicated by the arrow in Fig. 2. The parameters at 6 GeV and the magnet specification are listed in Table 1 and Table 2.

Table 1: Booster Parameters

Parameter	Value
Periodicity	8
Circumference	300 m
Harmonic Number	500
Straight Length	4.64 m
Working Tune	(17.18, 15.30)
Natural Chromaticity	(-27.74, -19.38)
Horizontal Damping Partition	2.49
Momentum Compaction	2.14 10^{-3}
Energy Loss	6.94 MeV
Equilibrium Emittance	9.85 nm-rad
Equilibrium Energy Spread	2.51 10^{-3}
Horizontal Damping Time	0.69 ms
Vertical Damping Time	1.73 ms
Longitudinal Damping Time	3.40 ms

The dynamic aperture with the tune diffusion rate and the tune spread envelopes are examined and shown in Fig. 3 and Fig. 4. The tune diffusion rate is defined as $\log_{10}\sqrt{\Delta\nu_x^2 + \Delta\nu_z^2}$ with the tune difference between the first and second 128 turns. The resonance at $x = 15$ mm is

Table 2: Magnet Specification ($K_2 \equiv \partial^2 B_z/\partial x^2/B\rho$)

Magnet	BD	QF	BM	QM	Q1	Q2
L (m)	2.20	0.50	0.98	0.22	0.28	0.40
B_0 (T)	1.19		1.33			
K_1 (m^{-2})	-0.45	1.81		-1.46	1.97	-1.54
K_2 (m^{-3})	-6.33	8.49				

due to $2\nu_x + 2\nu_z = 65$ which is not harmful. Meanwhile a systematic fifth order resonance is hit at $z = 11$ mm.

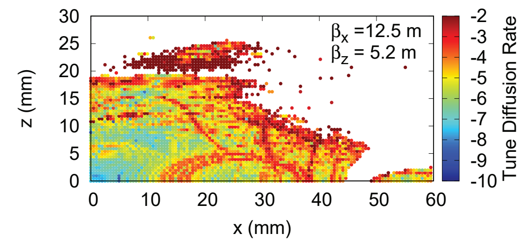

Figure 3: On-momentum dynamic aperture without errors.

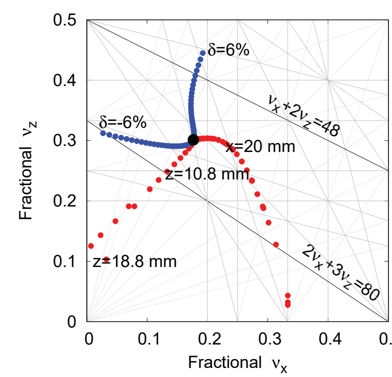

Figure 4: Tune spread envelopes in the tune diagram.

DISCUSSION

With the proper design of the constraints and the objectives, the PMSOEA does a good job on supervising the lattice construction and optimization of the objectives. Satisfactory solutions for the PETRA IV booster are obtained. In the future, this method can also be used to design a diffraction limit storage ring. If the particle tracking is needed, the program needs to be parallelized in a cluster to boost the performance.

To make the algorithm more intelligent, more ingredients of the knowledge about the problem can be added. For example, the concern about the working tune can be implemented into the dominance constraints. In a diffraction limit storage ring design, the betatron functions in the ID section has to be optimized. If -I scheme is used, proper phase advances between some positions must also be included. The constraints being stringent or relaxed, that is the question. How to properly design the constraints and objectives of the algorithm? This is an artisan work. It depends on the own physics of the specific problems and, of course, the taste of the designer.

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