

# OPTIMIZATION OF MULTI-TURN INJECTION INTO A HEAVY-ION SYNCHROTRON USING GENETIC ALGORITHMS

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## Abstract

For heavy-ion synchrotrons an efficient multi-turn injection (MTI) from the injector linac is crucial in order to reach the specified currents using the available machine acceptance. The beam loss during the MTI must not exceed the limits determined by machine protection and vacuum requirements. Especially for low energy and intermediate charge state ions, the beam loss can cause a degradation of the vacuum and a corresponding reduction of the beam lifetime. In order to optimize the MTI a genetic algorithm based optimization is used to simultaneously minimize the loss and maximize the multiplication factor (e.g. stored currents in the synchrotron). The effect of transverse space charge force on the MTI has also been taken into account. The optimization resulted in injection parameters, which promise a significant improvement of the MTI performance for intense beams in the SIS18 synchrotron at GSI.

## INTRODUCTION

The main goal during the design phase and later during operation of accelerators is to optimize and improve their performance. Unfortunately, accelerator problems are multi-dimensional, nonlinear, multi-objective and the quantities to be improved are often contradicting - improving one objective means worsening the others. A new approach to solve such difficult but realistic problems is the use of genetic algorithms (GA) [1, 2]. The advantage of these optimization methods is that they allow finding globally optimal solutions with a large number of fit parameters, while showing the trade-offs in objective functions within a reasonable computing time. Over the years GA have been applied to optimize the performance of several accelerators.

In order to increase the space charge limit, heavy-ion synchrotrons are operated with intermediate charge state ions [3]. Therefore stripping injection is not an option and the MTI has to respect Liouville's theorem for the chosen charge state avoiding the already occupied phase space area. The MTI performance depends on various machine and beam parameters as well as on the contradicting quantities to be improved like multiplication of the injected current, the loss during injection and the required linac brilliance. Therefore, GA is well suited to optimize the injection.

## GENETIC ALGORITHMS

Genetic algorithms are inspired by natural evolution. GA search for solutions using techniques such as *selection*, *mutation* and *crossover*. Due to the wide range of different algorithms GA are very flexible and can be adapted to a large range of different problems.

In GA terminology, a solution vector is called an *individual*

and represents a set of variables; one variable is a *gene*. A group of individuals form a *population*, the following child populations are counted in *generations*. The first generation is created randomly. The crossover operator exchanges variables between two individuals - the parents - to discover with their offspring promising areas in the solution space. For the optimization within a promising area the mutation operator randomly changes the characteristics of individuals on the gene level. Reproduction of the individuals for the next generation involves selection. The *fitness* of an individual reflects how well an individual is adapted to the optimization problem and determines the probability of its survival for the next generation. The fitness is evaluated by the objective function, by a simulation code or by a real running system. During the single-objective optimization the most promising individuals are chosen to create the next generation. By allowing individuals with poor fitness to take part in the creation process the population is prevented to be dominated by a single individual. The most popular techniques are proportional selection, ranking and tournament selection [1, 2]. In many real-life problems, multi-quantities have to be optimized. In addition, these quantities can be contradicting and there are more than one equally valid solutions. These solutions form a so-called *Pareto front* (PA front) in the solution space, see Figure 1. A solution is Pareto optimal if it is not dominated by any other solution. By using a non-dominated selection algorithm, one tries to find solutions near the optimal Pareto set. NSGA2 and SPEA2 are the most popular non-dominated selection algorithms.

As the SIS18 MTI model has been implemented in the particle tracking code pyORBIT - the python implementation of the ORBIT (Objective Ring Beam Injection and Tracking) code - and was carefully validated against experiments [4, 5],

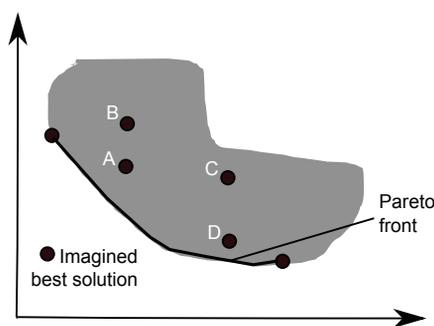


Figure 1: The Pareto front in the solution space. The solution A and D are located near the Pareto front and non-dominated, while the solutions B and C are either dominated by the solution A or D. The solutions B and C do not dominate.

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the choice to use the Distributed Evolutionary Algorithms in Python (DEAP) together with pyORBIT was obvious. DEAP works in perfect harmony with parallelization mechanisms such as multi-processing. DEAP includes evolution strategies, multi-objective optimization, and allows the development of new genetic algorithms [6]. DEAP decouples the GA operators like crossover from the evolutionary algorithms, which allows for example to easily exchange the selection operator and leave the remaining algorithm unchanged.

## THE OPTIMIZATION PROBLEM MTI

In the SIS18 the injected beamlets are stacked in the horizontal phase space until the machine acceptance is reached. To fulfill Liouville's theorem, four bumper magnets create a time variable closed orbit bump such that the electrostatic injection septum deflects the next incoming beamlet into free horizontal phase space close to the formerly injected beamlets. During the injection loss can occur on the septum and acceptance. If  $\eta$  characterizes the ratio between lost and injected particles, the multiplication factor (i.e. accumulated beamlets) follows to

$$m = n(1 - \eta). \quad (1)$$

$n$  is the ratio between injection and revolution time. For a loss-free injection  $\eta$  is zero and the multiplication factor  $m$  is equal to the number of injected turns  $n$ .

To achieve high beam intensities the injected beamlets should be packed as compact as possible. In normalized phase space coordinates, the injected beamlets as well as the acceptance are approximately circular, therefore the MTI packing problem is similar to the packing of ropes and cables. We assume that  $m$  beamlets with radius  $a$  are hexagonally packed into a given machine acceptance  $A$  with radius  $R$ , then the number of beamlets is [7]

$$m = \frac{2\sqrt{3} R^2}{\pi d a^2} \sim \frac{2\sqrt{3} A_x}{\pi d \epsilon_x}. \quad (2)$$

The dilution factor  $d$  is larger than one. Previous MTI optimization studies [8–10] and the above equation demonstrate clearly that the horizontal emittance of the incoming beam has a significant impact on MTI performance. The smaller the injected emittance is, the better the MTI performance gets. A reduction of the horizontal emittance can be achieved by horizontal collimation [9] or by a round-to-flat transformation [10].

The goal is to achieve the space charge limit in the synchrotron. Therefore besides a large multiplication factor also the injected current  $I_0$  must be large. In particular the product of both must be the corresponding beam intensity

$$N = m \frac{I_0}{q f_0} \quad (3)$$

determined by the allowable space charge tune shift of the synchrotron.  $f_0$  is the revolution frequency at injection en-

ergy and  $q = Ze$  the charge of the injected ion. The ratio of required injected current and emittance is the non-normalized linac brilliance

$$B_x = \frac{I_0}{\epsilon_x}. \quad (4)$$

The linac brilliance must be adapted to gain a high MTI performance and should be as large as possible. On the other hand the required linac brilliance must be achievable for the injector linac and therefore should be small.

The beam parameters from the injector linac and also the MTI adjustment must be well adapted for an excellent MTI performance and must respect the limiting technical and physical conditions. During the GA optimization the parameters on which the MTI depends are altered. These parameters are the injected beam emittance  $\epsilon_x$ , the amplitude  $x_0$ , the angle  $x'_0$  of orbit bump, the position of the incoming beam at the septum  $x_0, x'_0$ , the mismatch of the beta function  $M$ , the ramping rate  $\tau$  for an exponential ramp and the number of betatron oscillations per turn  $Q_x$ . For the reasons indicated above the optimization goals of the MTI performance are defined as:

$$\text{minimize } \eta(n, \epsilon_x, x_c, x'_c, M, x_0, x'_0, \tau, Q_x, \dots) \quad (5)$$

$$\text{maximize } m(n, \epsilon_x, x_c, x'_c, M, x_0, x'_0, \tau, Q_x, \dots) \quad (6)$$

$$\text{minimize } B_x(n, \epsilon_x, x_c, x'_c, M, x_0, x'_0, \tau, Q_x, \dots). \quad (7)$$

The beam loss induced increase of the dynamic vacuum pressure and the resulting reduction of the beam lifetime for intermediate charge ions are the main limitation for the extracted beam intensity from the SIS18 [9]. Therefore the first aim for the improving the MTI performance is to reduce the loss for a constant number of injected turns and a given injected emittance. Figure 2 shows the evolution of the loss for a variation of the number of injected turns (10, 15 and 20). Between the 5th and the 10th generation for a tournament selection and 500 individuals the GA finds a better

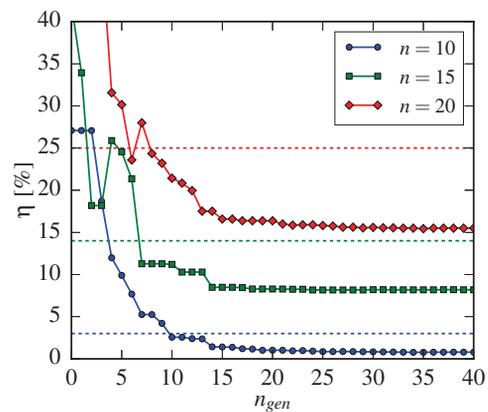


Figure 2: The evolution of loss for injected emittance of 7 mm mrad. GA found a much better injection parameter setting for a low loss injection than the previous studies (indicated by the dashed horizontal lines).

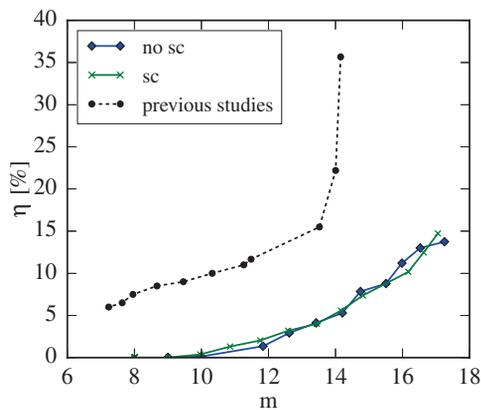


Figure 3: The PA front for the multiplication factor and MTI loss. GA found a much better PA front than the previous studies. Space charge leads to a more optimal PA front.

set of variables with lower losses than the previous studies (indicated by the dashed horizontal lines [4]). After the 15th generation the almost fittest individual is found. The fact that a longer injection time leads to higher loss is also exists for the GA optimization if the available acceptance is almost occupied. However, especially in these cases the GA discovers a much better solution.

The next step to improve the MTI performance is to include the multiplication factor besides the beam loss into the optimization process, i.e. to find a 2D PA front. For this purpose, the genome of each individual has been increased by a gene integer variable, which represents the number of injected turns. In order to minimize the simulation time the number of injected turns has to be limited to values from 8 – 20. The injected emittance was 7 mm mrad. Evaluating only new individuals can further reduce the optimization time. This is already included in the DEAP package. Figure 3 shows GA finds a much better set of parameters for an improved MTI performance than the previous studies [4]. The influence of space charge on the optimization of the MTI performance with GA is significant even if the discover PA fronts are similar: The discovered MTI parameters are different with space charge. With GA optimization the incoming beamlets are stacked very compact, which can lead to increasing space charge tune shift during the injection. Therefore the characteristic shift of the optimum tunes with space charge is possibly no longer determined by the tune shift of the injected beam as proposed in [4]. The stability of the solution discovered with GA has also been investigated. Small changes (< 5%) on the MTI adjustment parameters without space charge effects lead only to a slightly worse PA front. For an excellent MTI performance also the linac brilliance has been included in the optimization process, i.e. to find a 3D PA front. Figure 4 shows in accordance with the MTI model and previous studies the trade-off between the objectives over a wide range of parameter variations, which can be summarized as follows: Small loss means small multiplication factor or small injected emittance; a high multiplication

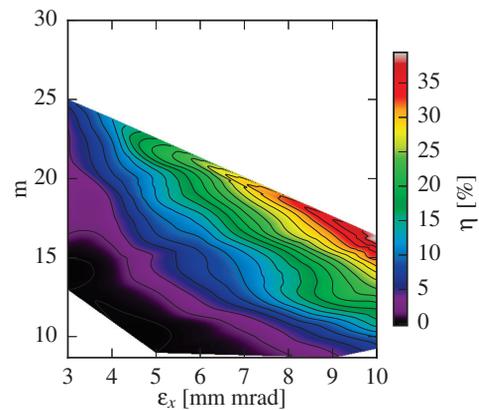


Figure 4: The 3D Pareto front for a injected current of 15 mA without space charge effects. GA has been optimized simultaneously the multiplication factor, loss and brilliance.

factor implies small emittance or large loss for medium size emittance; and large emittance means very large loss or small multiplication factors. The obtained results for the single and double objective optimizations for no space charge effects are located also on the 3D PA front.

## OUTLOOK

The GA optimization resulted in injection parameters which promise a significant improvement of the MTI performance. The influence of space charge on the MTI performance will be further investigated. To fulfill the required extracted beam intensity from SIS18, the beam loss induced vacuum degradation and the resulting reduction of the beam lifetime will also be taken into account in future studies. For a real working accelerator the multi-objective optimization is in most cases not possible due to the long optimization time required, since the evaluation of the fitness function cannot be performed simultaneously. To improve the efficiency of the optimization with regard to optimization time, one can try to use a smaller number of individuals and generations, including additional constraints or start the GA optimization with individuals produced by a previous simulation [11]. An optimization of the single objective MTI loss with GA during acceptable optimization time is feasible, if the cycle time of the SIS18 synchrotron can be significantly shortened and a small pre-optimized population can be used. The effect of a very small population, the creation of a population from a previous, small different optimization problem and the influence of the beam distribution fluctuation on the optimization of the MTI performance must be further investigated.

## REFERENCES

- [1] A. Hofler et al., "Innovative applications of genetic algorithms to problems in accelerator physics", PRST-AB 16 010101 (2013)
- [2] A. Konak et al., "Multi-objective optimization using genetic algorithms: A tutorial", RELIAB ENG SYST SAFE 91, 992 (2006)

- [3] P. Spiller et al., FAIR Technical Design Report (2008)
- [4] S. Appel et al., "Multi-turn injection into a heavy-ion synchrotron in the presence of space charge", arXiv:1403.5972v1 (2014)
- [5] pyORBIT, <https://code.google.com/p/py-orbit>
- [6] F. Fortin et al., "DEAP: Evolutionary algorithms made easy", JMLR 13 2171-2175, (2012)
- [7] S. Kravitz, "Packing cylinders into cylindrical containers", Mathematics magazine 40 (2) (1967).
- [8] S. Appel, "Simulation of the multi-turn injection efficiency for flat injected beams", GSI Report 2013-03 (2013).
- [9] Y. el Hayek, "Initial beam loss and control of dynamic vacuum effects in SIS18" in Proc. of IPAC 2013
- [10] L. Groening et al., "Demonstration of flat ion beam-creation and -injection into a synchrotron" in Proc. of IPAC 2015
- [11] B. Terzic et al., "Simultaneous optimization of the cavity heat load and trip rates in linacs using a genetic algorithm", PRST-AB 17 101003 (2013)