

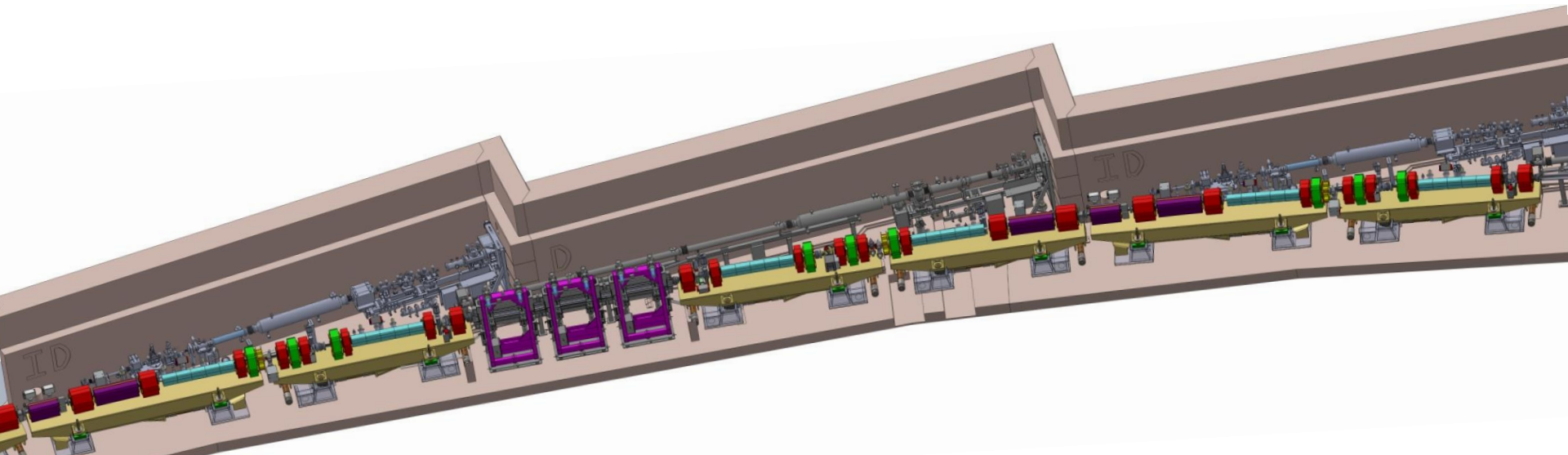


The European Synchrotron

Optimization of the ESRF upgrade lattice lifetime and dynamic aperture using genetic algorithms

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11/03/2015



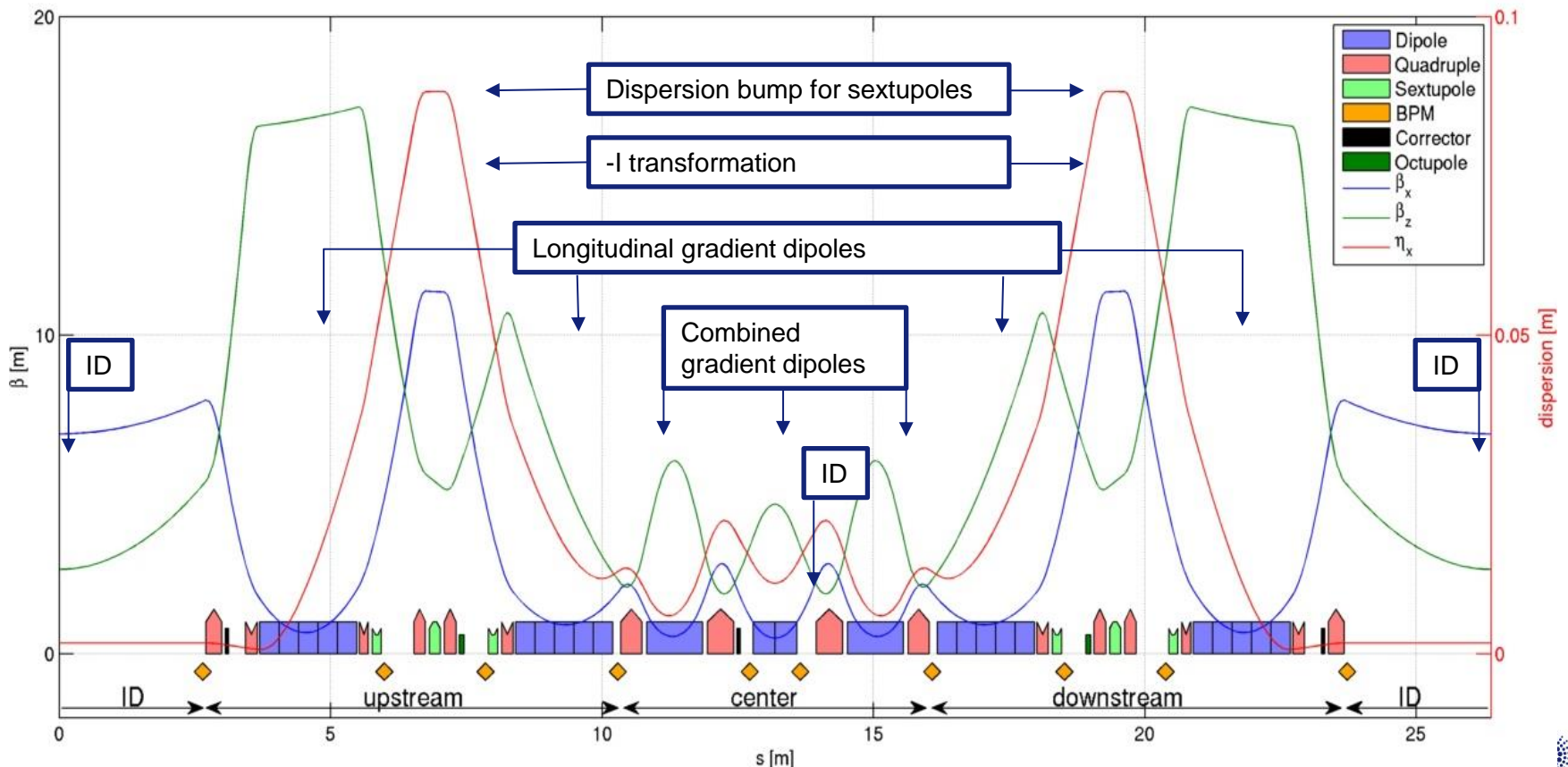
- **ESRF upgrade**
- **Injection efficiency and Touschek lifetime**
- **Why a multi-objective optimization**
- **A popular multi objective genetic algorithm: NSGA II. How it works.**
- **ESRF upgrade lattice optimizations using NSGA II algorithm**
- **Other optimization methods**
- **Conclusions**

ESRF UPGRADE: NORMAL CELL

ESRF upgrade has a 7 bend achromat cell, also called hybrid multi bend achromat (HMBA) cell.

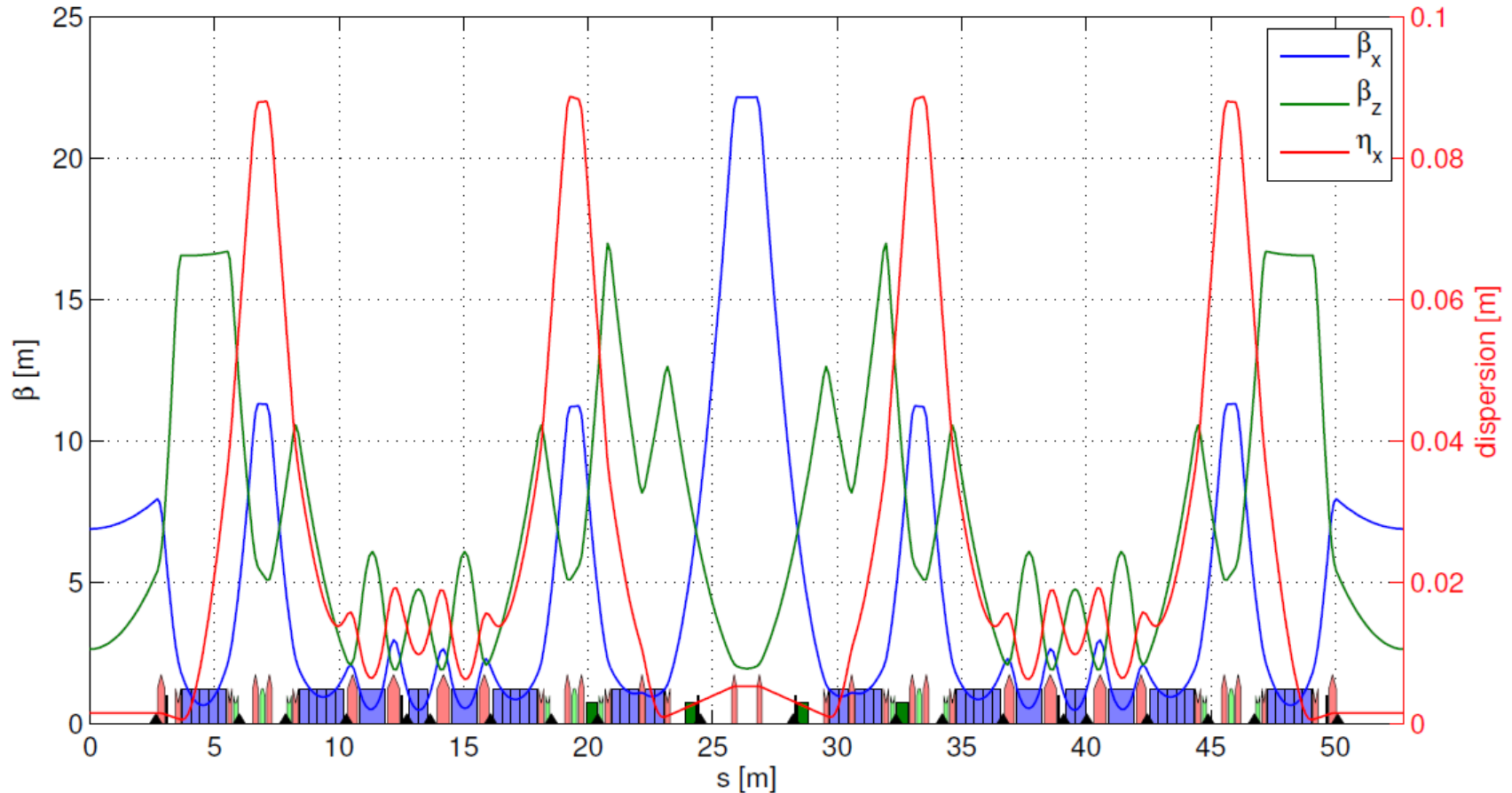
The equilibrium emittance will be ~ 130 pm, from the present 4 nm.

Touschek lifetime and injection efficiency are two of the most important challenges for the upgrade lattice.



Two cells will provide a bump in horizontal beta function, in order to increase the dynamic aperture.

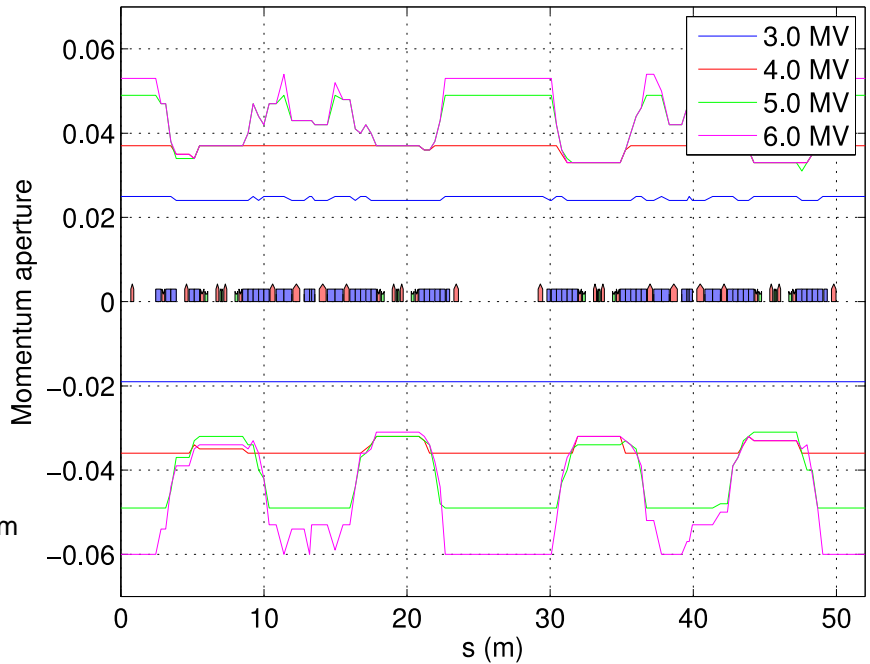
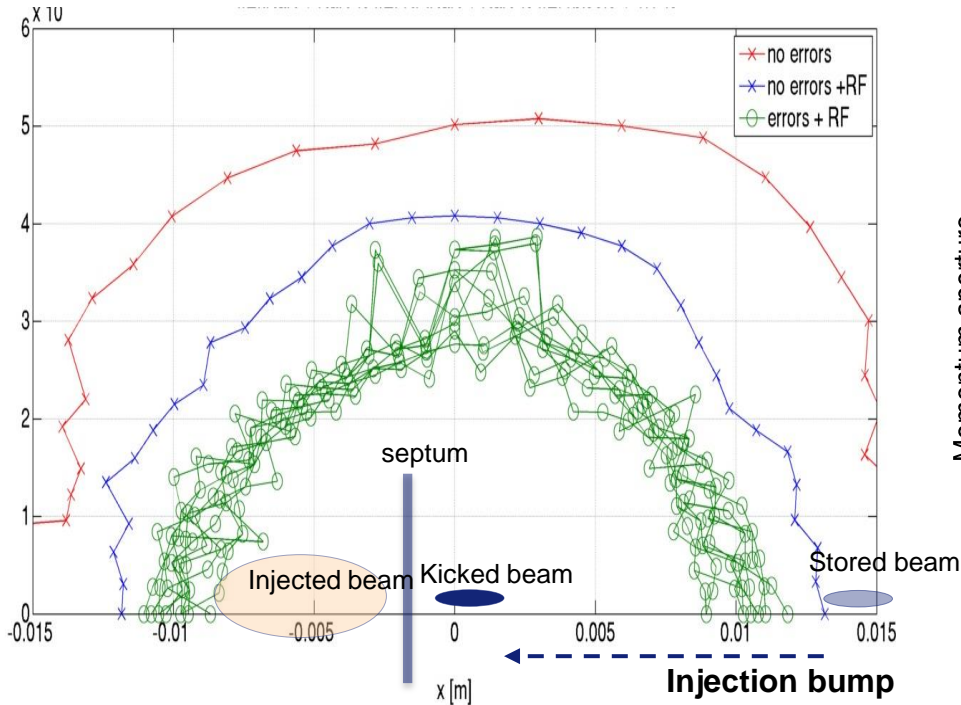
$v_x = 4.763$ $\delta p/p = 0.000$
 $v_z = 1.709$ 1 period, $C = 52.749$



Injection efficiency depends on the dynamic aperture.

Touschek lifetime depends on the momentum aperture:

$$\tau_t \propto \frac{\sqrt{\epsilon_y} \sigma_z}{I_b} \delta_{acc}^3$$



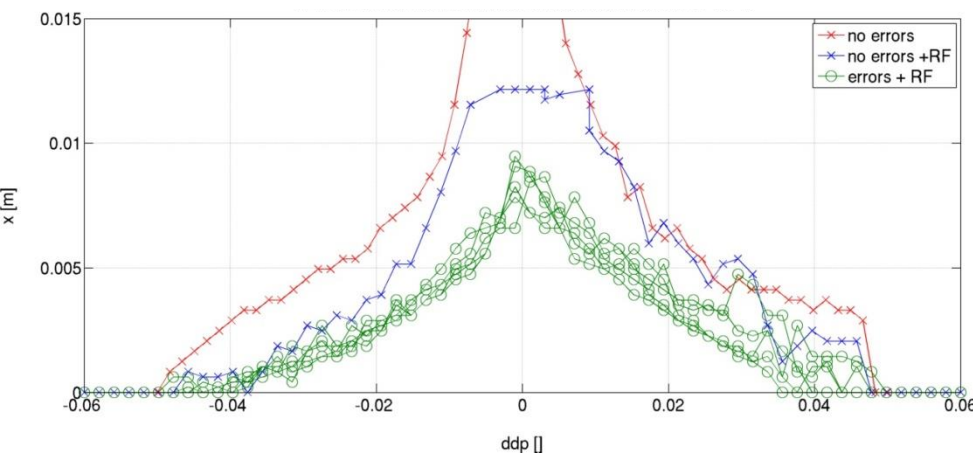
On-energy dynamic aperture and momentum aperture depend on the linear and nonlinear lattice.

Dynamic aperture computation is about 1h, momentum acceptance about 2-3h.

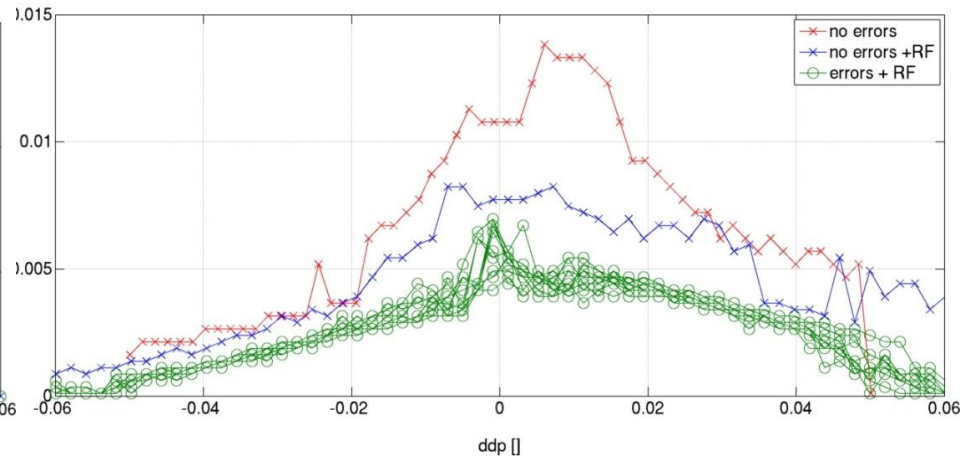
For accelerator lattice design, we need to maximize the injection efficiency and the beam lifetime.

We can have large on-momentum dynamic aperture, but small momentum acceptance.

Large dynamic aperture



Large momentum acceptance



We want to optimize linear and nonlinear lattice, in order to increase both dynamic aperture and momentum acceptance.

A multi-objective optimizer could be helpful.

NSGA II has been developed by K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan in 2002.

NSGA II means Non-dominated Sorted Genetic Algorithm 2.

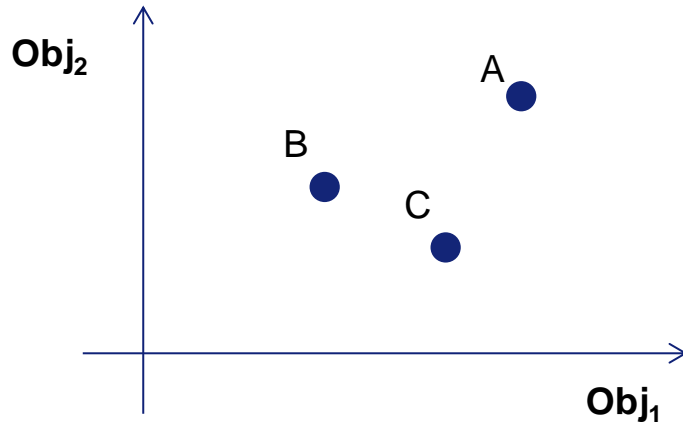
“A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II”, IEEE Transactions on evolutionary computation, vol. 6, no. 2, April 2002

NSGA II is used in many different fields, for many different problems.

In accelerator physics, it is used in many laboratories.

The algorithm is implemented in many codes.

The sorting is based on non-domination.



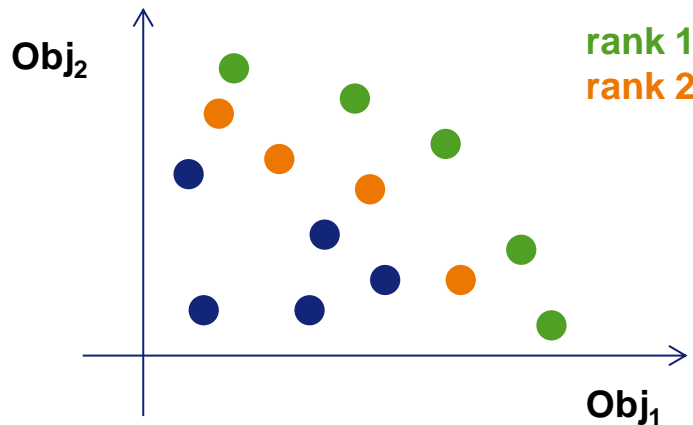
B and C are dominated by A, because

$$\text{Obj}_1(A) > \text{Obj}_1(B,C)$$

and

$$\text{Obj}_2(A) > \text{Obj}_2(B,C)$$

Ranking



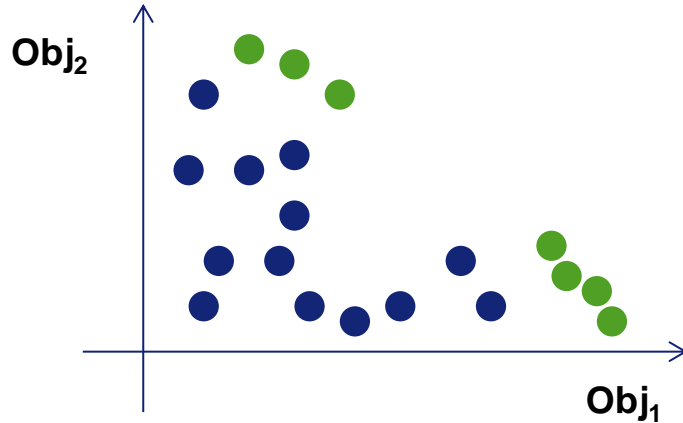
Green elements are the non-dominated ones.

They are called the non-dominated front or the Pareto front.

The Pareto front has rank 1.

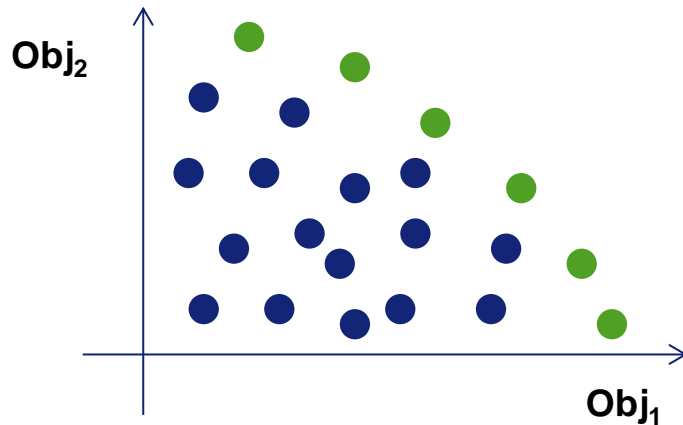
Orange elements are dominated by one or more green elements and they have rank 2.

Crowding distance



Not crowded solutions in the Pareto front are better.

A crowding distance (dist) can be defined per each element. It measures the distance between the element and the neighbors with the same rank.



Element A is better than B:

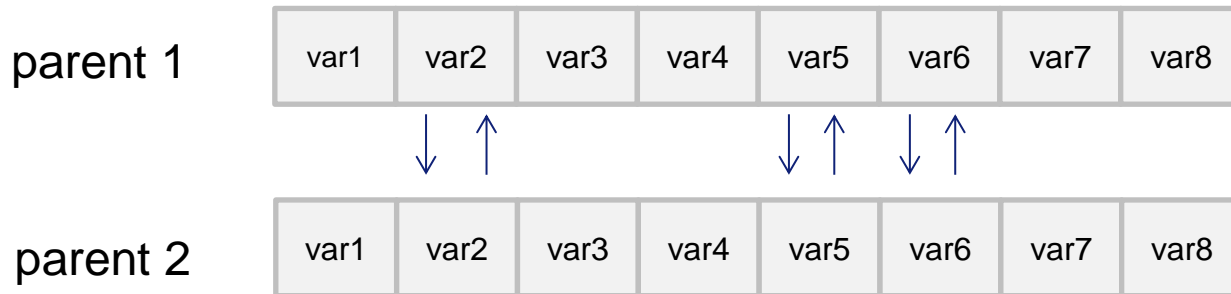
If $(\text{rank}(A) < \text{rank}(B))$

OR

$(\text{rank}(A) = \text{rank}(B)) \text{ AND } (\text{dist}(A) > \text{dist}(B))$

The evolution of the population is made with the genetic operations:
From two parents we obtain two children using cross over and mutation

Cross over



A fraction of the variables are switched between the two parents

Mutation

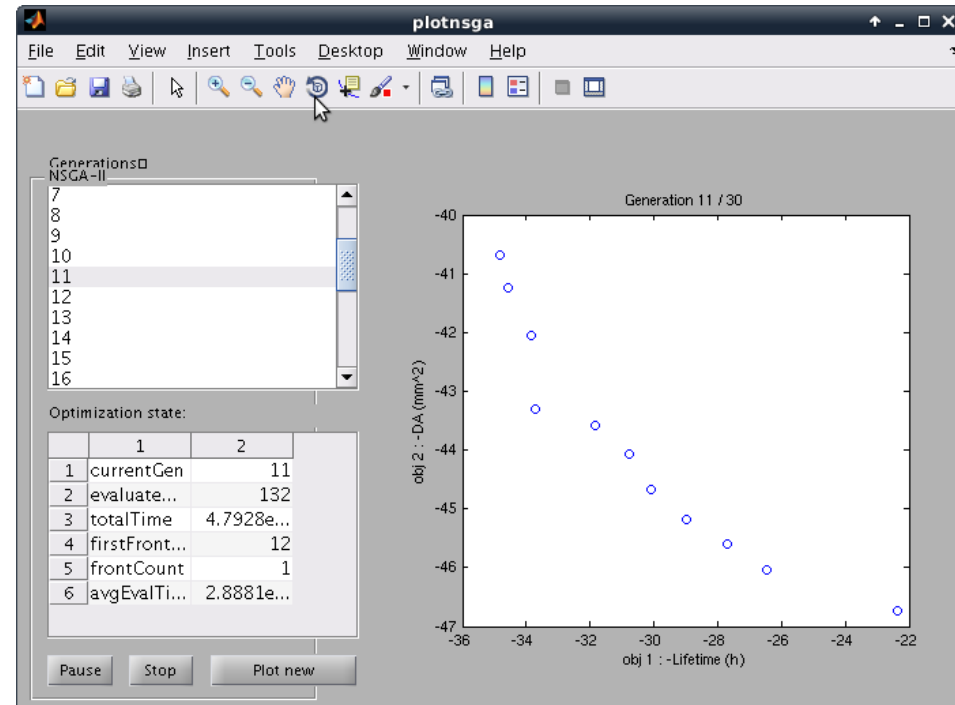
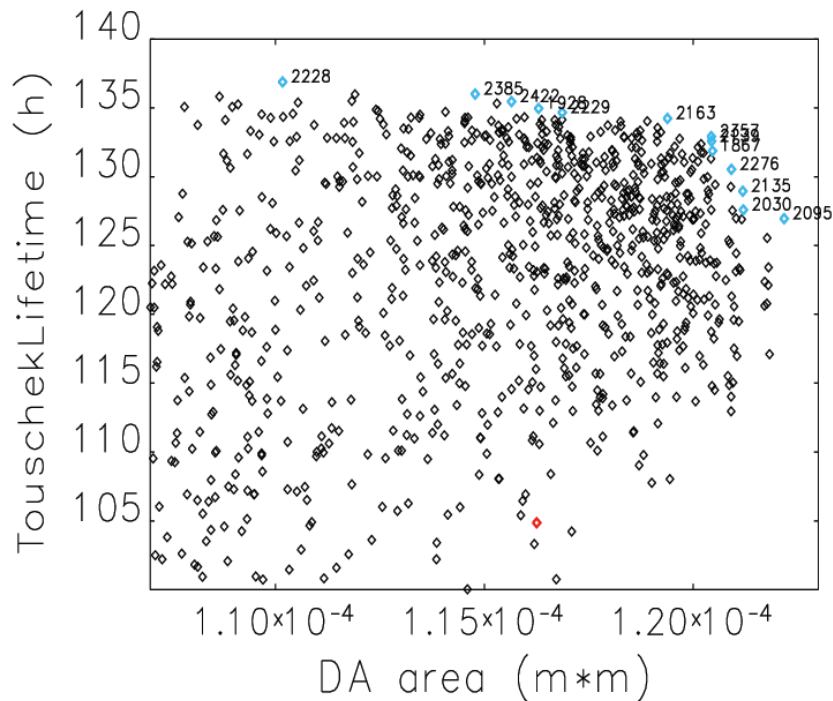
After the cross over, some random mutations of some of the variables are added.

Once we have the two children, we can compute for them the objective functions and we can sort again.

IMPLEMENTATIONS OF NSGA II ALGORITHM

geneticOptimizer: a script distributed with elegant, written by Michael Borland

NGPM: a matlab program available on internet, written by Song Lin



Possible variables

Sextupole magnets: 6 per cell; periodicity can be 1 or more cells.

Octupole magnets: 2 per cell;

Chromaticities;

Tunes;

Phase advances between sextupoles;

Beta and alpha functions in some locations of the cell.

Objective functions

On-momentum dynamic aperture

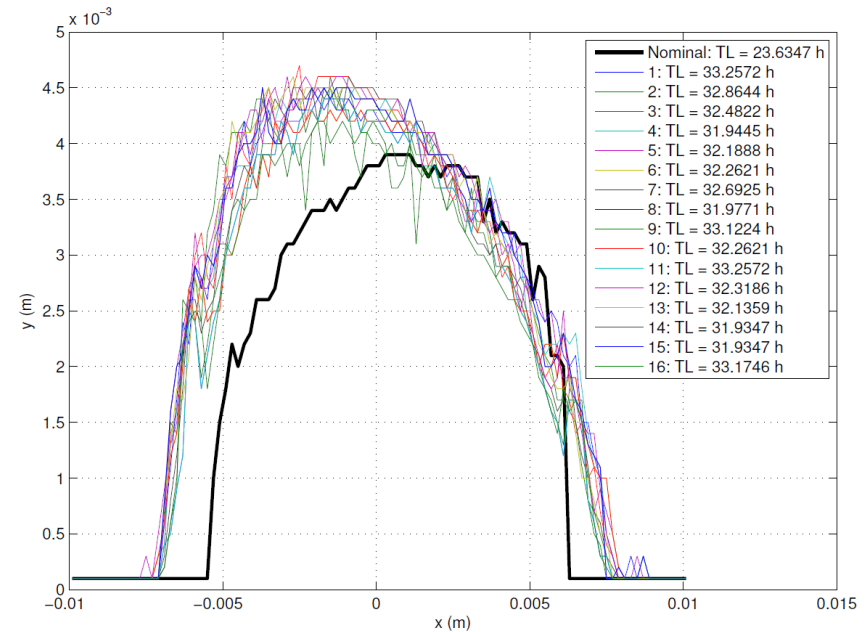
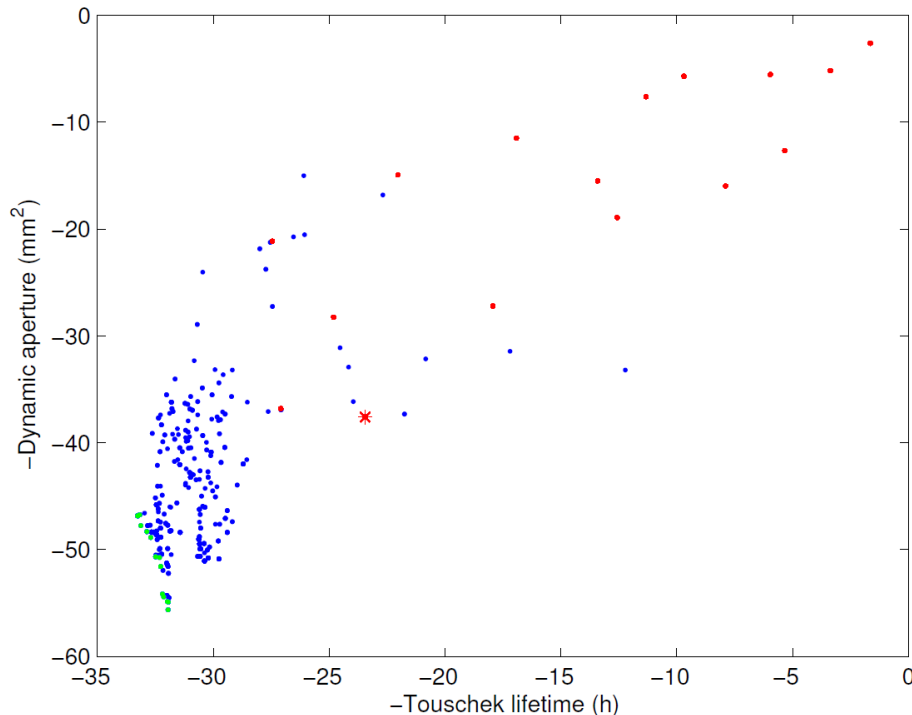
Touschek lifetime computed with Piwinski formula

All the tracking is done with matlab Accelerator Toolbox

PERFECT LATTICE OPTIMIZATIONS (1)

We saw from a chromaticity scan that high horizontal chromaticity was good for Touschek lifetime.

Sextupole and octupole optimization with fixed vertical chromaticity, but free horizontal one.

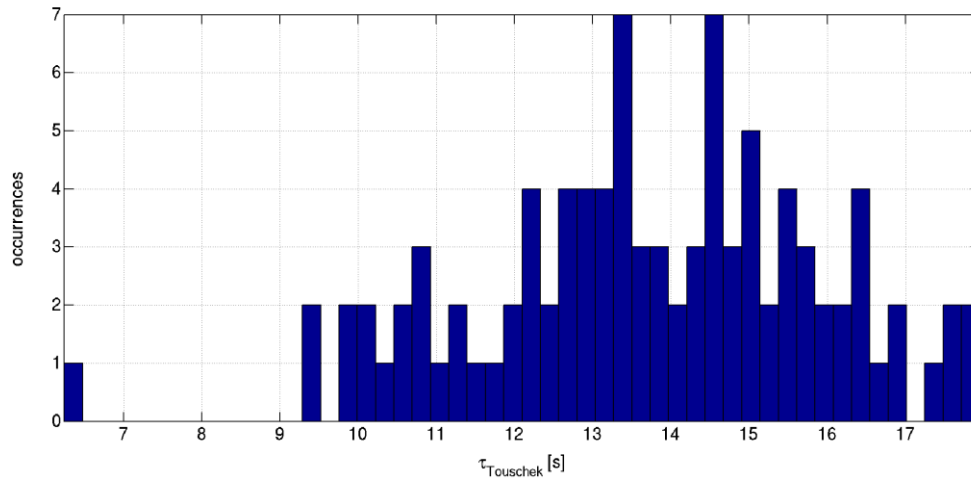


The Pareto front had very high horizontal chromaticity $\xi_x \sim 15$

PERFECT LATTICE OPTIMIZATIONS (2)

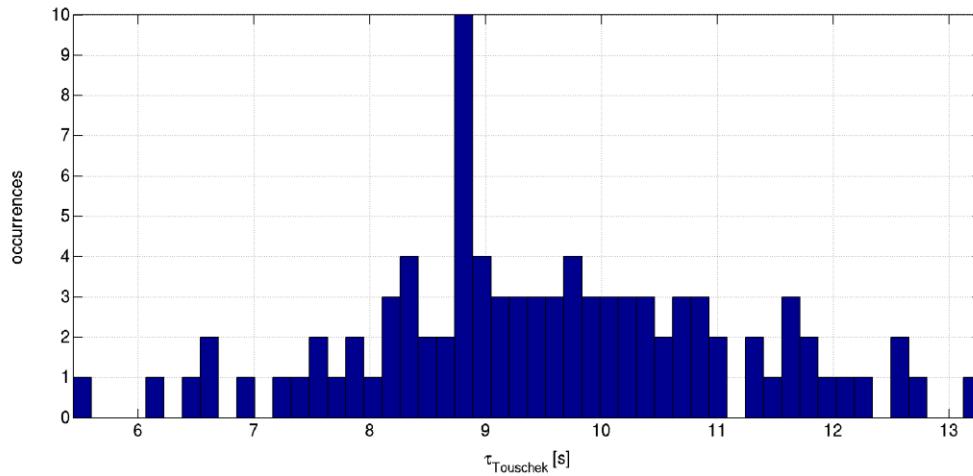
We tested one result with 100 error seeds and we got bad results

latfilenoinj nt512 ns0100 0001 NominalNoInj TDSlist (100 seeds)
 τ_{Touschek} median: 1.37e+01 τ_{Touschek} mean: 1.37e+01 ,lost: 4 ,above: 0



Nominal lattice:
LT~14h

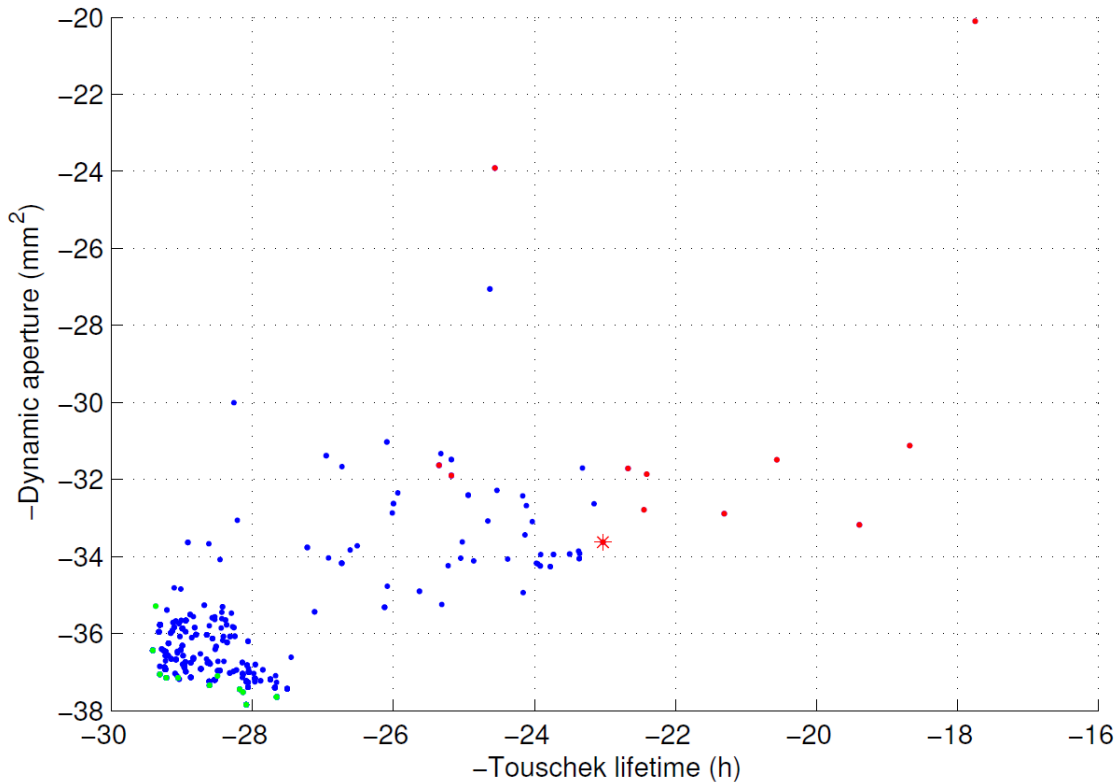
latfileLatt 827 nt512 ns0100 0001 Latt827 TDSlist (100 seeds)
 τ_{Touschek} median: 9.39e+00 τ_{Touschek} mean: 9.53e+00 ,lost: 8 ,above: 0



Optimized lattice:
LT~9.5h

Same optimization, with two free chromaticities.

Optimum values have positive chromaticities: 10-5.



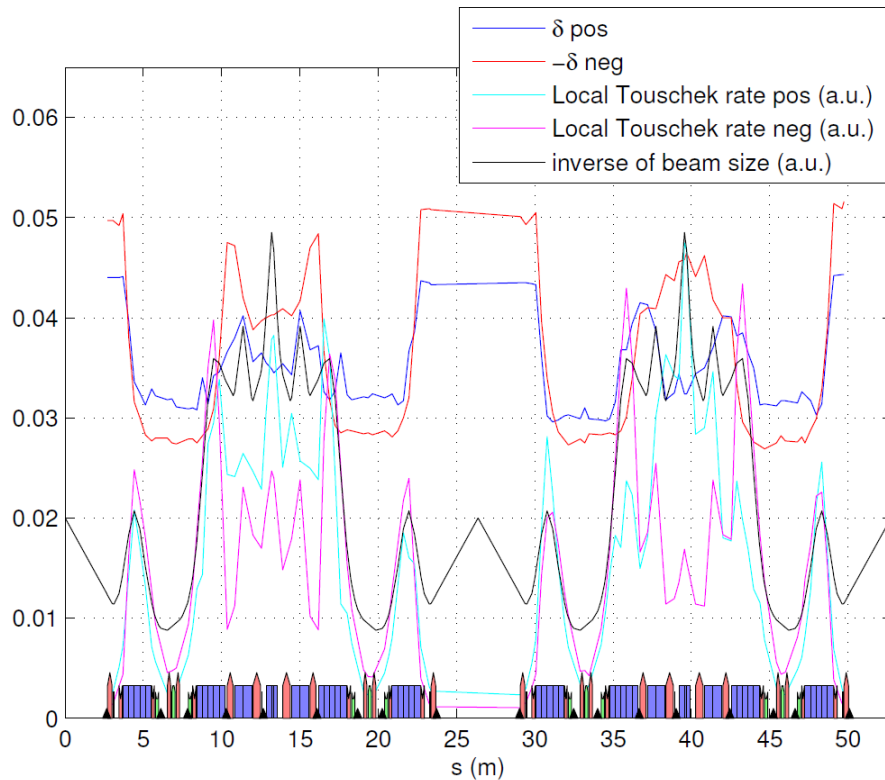
We started to do optimizations computing the objective functions on many seeds of errors, usually 10.

Each point in the plot is the average on 10 error seeds!

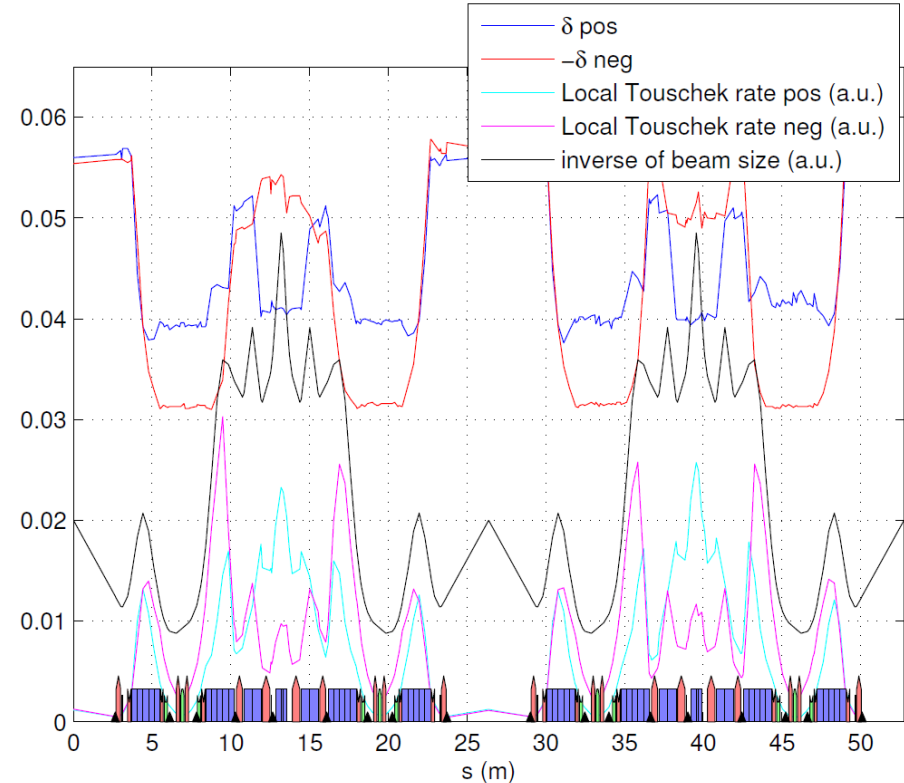
A very large computer power is needed.

To have ~300 different settings, we need to compute 300 times 10 dynamic apertures and 10 Touschek lifetimes:
 $300 \times 10 \times (1h + 2h) = 9000h$ with a single core, 18h with 500 cores.

Sextupole and octupole optimization of ESRF upgrade lattice.



Before sextupole optimization



After sextupole optimization

Momentum acceptance is increased where the beam size is smaller.

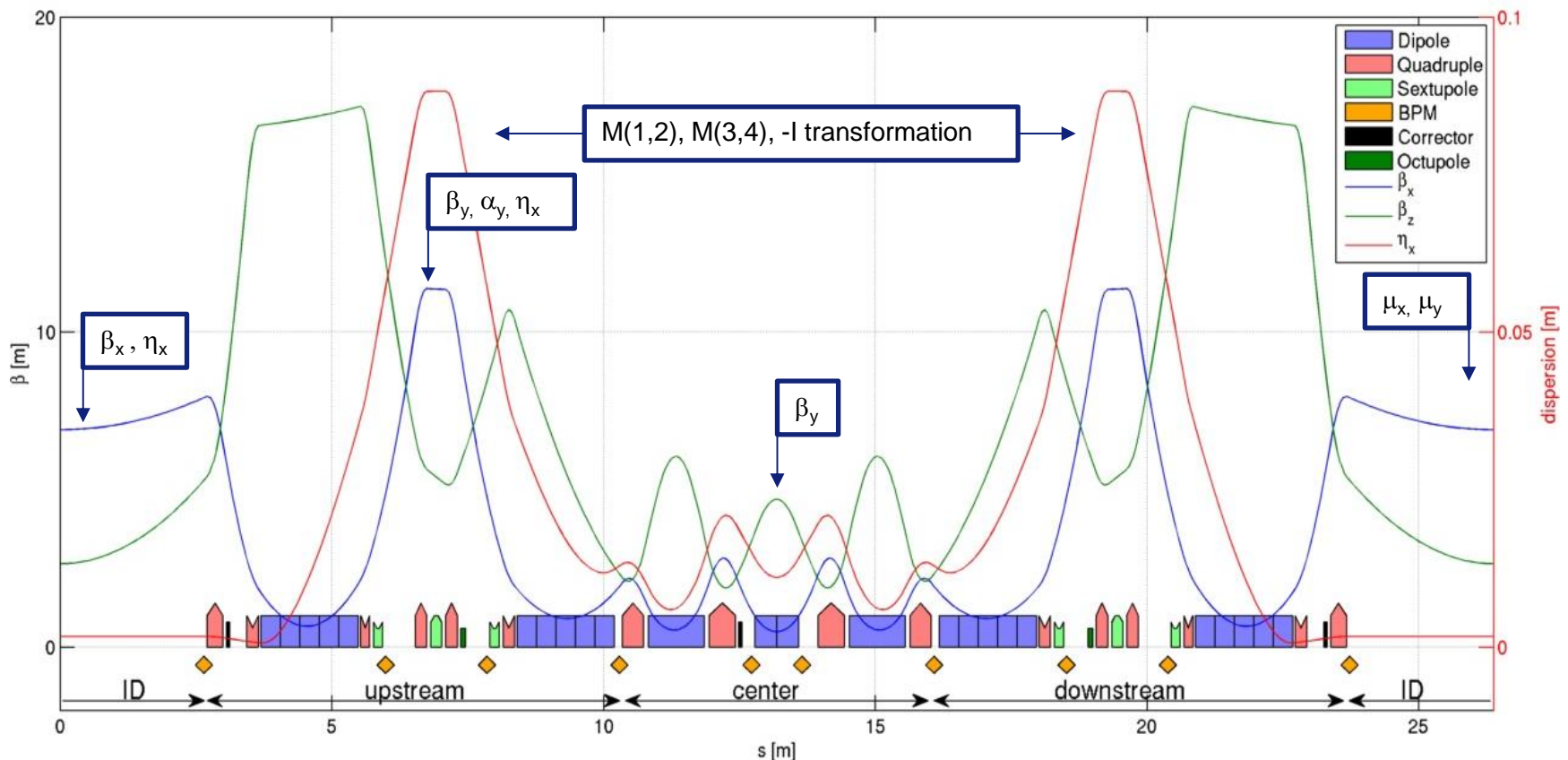
We normally use a NSGA II optimization to choose:

- Sextupole and octupole values
 - The number of sextupole and octupole families
 - The chromaticities
 - The size of the superperiod
-
- Linear lattice optimization

LINEAR LATTICE OPTIMIZATIONS

We optimize some linear parameters of the standard cell with NSGA II optimizations.

In this case, the variables are linear parameters together with nonlinear magnets.



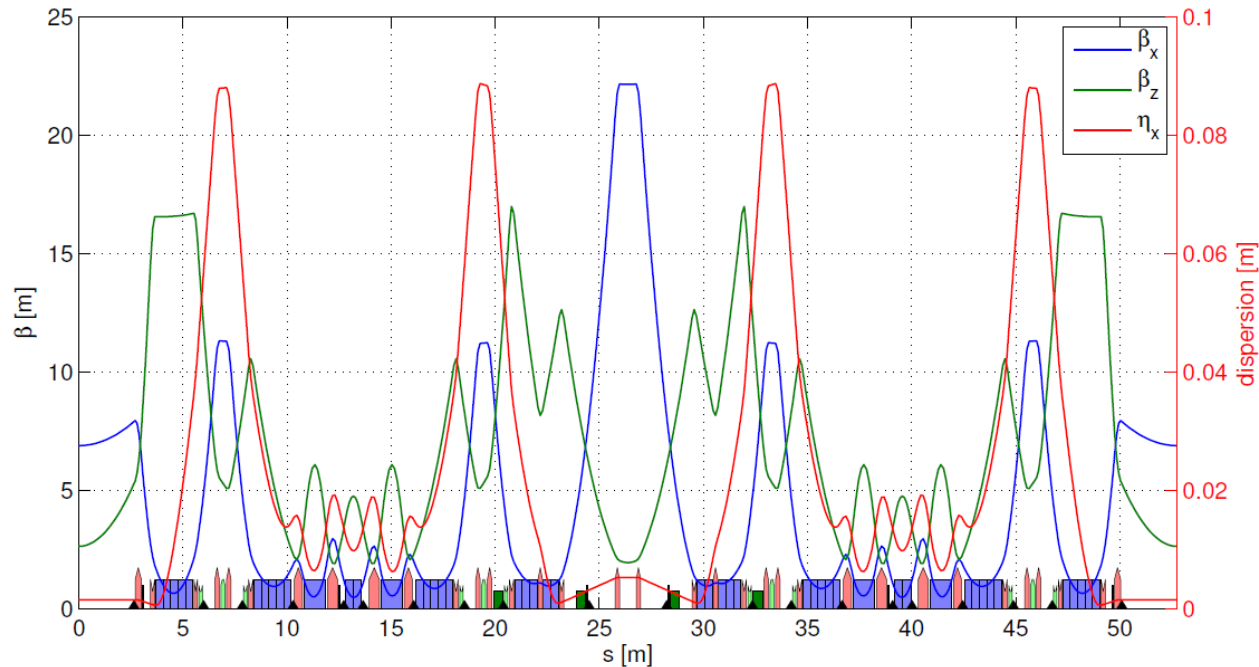
SEXTUPOLES OF INJECTION CELL

Phase advances between the sextupoles of the injection cell are slightly different than the ones in the other cells.

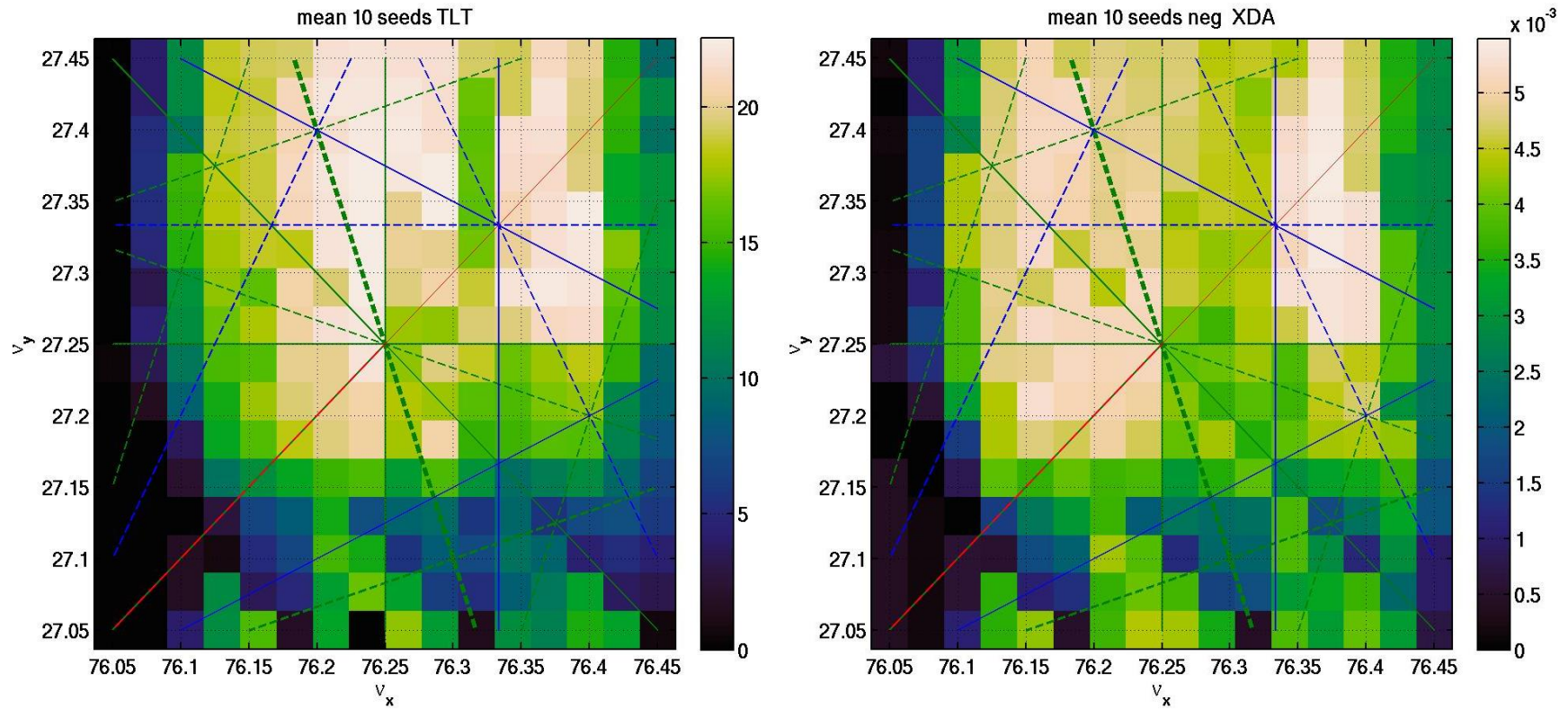
If we put the same sextupole values as the normal cells, we loose in momentum acceptance.

We can find the optimum values for the sextupoles of the injection cell with a NSGA II optimization.

$$\begin{aligned} v_x &= 4.763 & \delta p/p &= 0.000 \\ v_z &= 1.709 & 1 \text{ period, } C &= 52.749 \end{aligned}$$



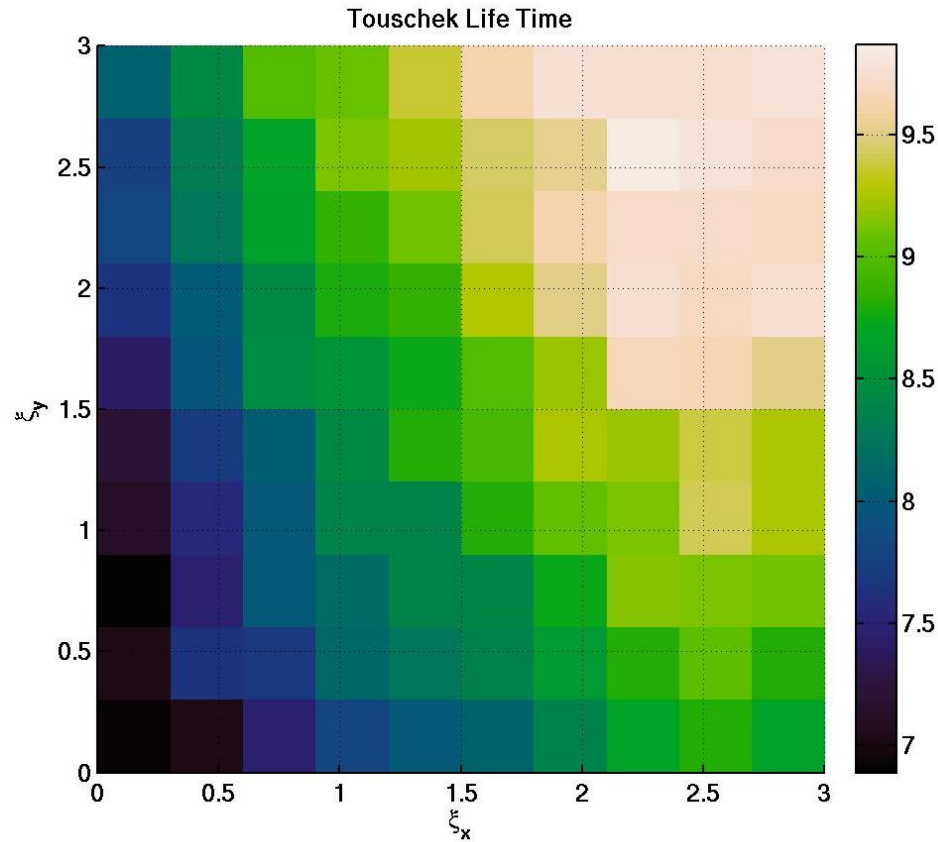
OTHER OPTIMIZATIONS: TUNE SCANS



In this figures: sextupoles optimized at (.23, .34) and no injection cell

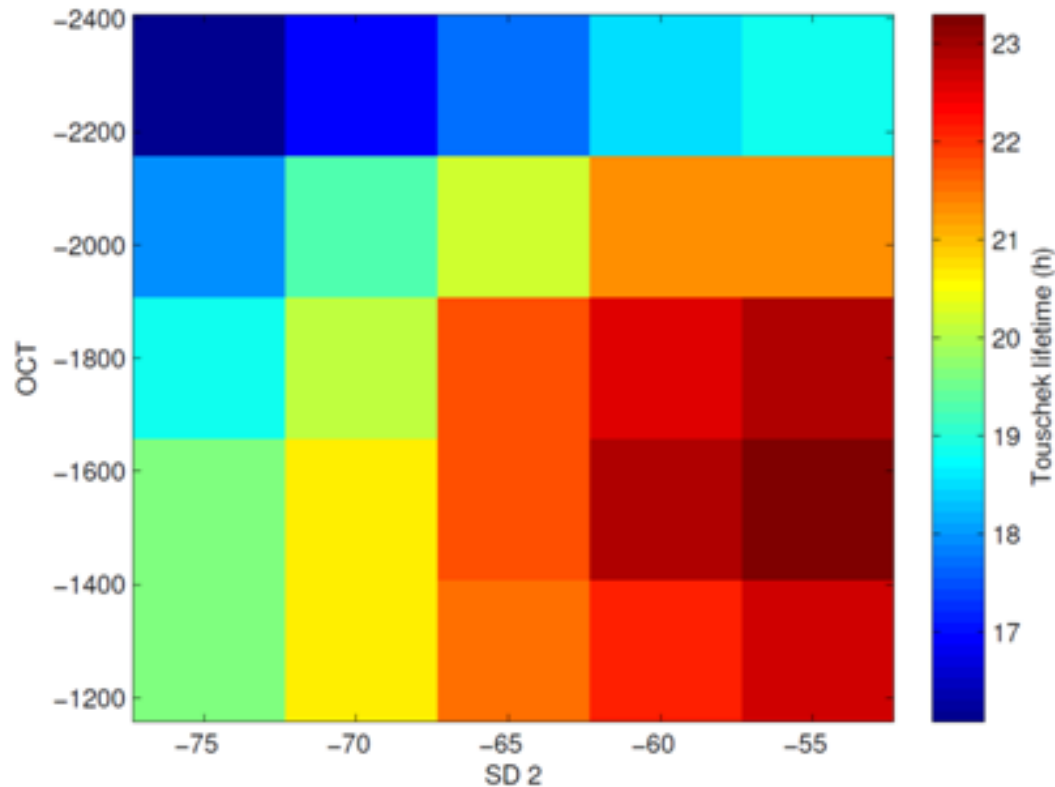
OTHER OPTIMIZATIONS: CHROMATICITY SCANS

More than one year ago, we saw that high chromaticity was good for lifetime with a 2D chromaticity scan.



OTHER 2-D SCANS

If we use only three sextupole families and one octupole family and we fixed the two chromaticities (6 and 4 in this case), we can scan the two left degrees of freedom in a 2D grid.



- The NSGA-II algorithm is very effective in finding linear and nonlinear lattice parameters, in particular for sextupole and octupole strengths.
- NGPM is a good implementation of the algorithm and can be used together with the matlab Accelerator Toolbox. It is easily parallelizable.
- Optimization of perfect lattices are faster, but adding errors you can have bad results.
- Optimization of lattices with many seeds of errors are better, but you need a big cluster.
- Many iterations between tune scans, chromaticity scans, other 2-D scans and NSGA-II optimizations are useful to find the best settings.

Many thanks for your attention

