First Application of MOGA to Improve the Touschek Lifetime of SOLEIL: Simulation and Experimental results

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Synchrotron SOLEIL

Second LER Lattice Design workshop

Outlook

1. Introduction

2. Qualification and benchmarking of ELEGANT/Tracy3

3. MOGA Results: Simulation and Measurements
    i. Simulated Results Analysis
    ii. Frequency Map Analysis as Selection Method
    iii. Beam-Based Experiments
    iv. Comparison of Simulated and Experimental Results

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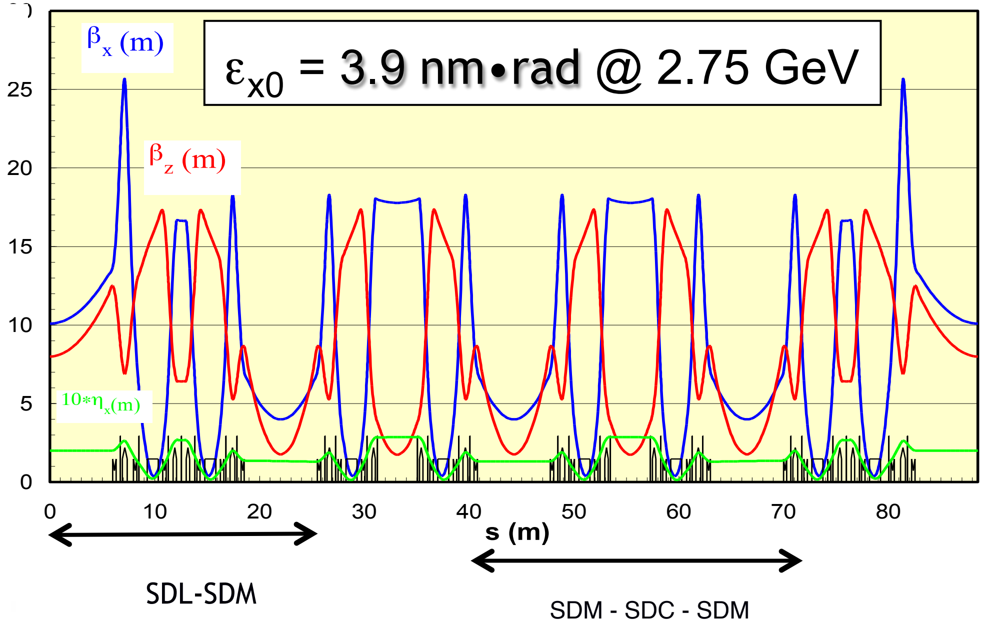
INTRODUCTION

Today's SOLEIL Lattice and main Challenges

Rather small Circumference: **354 m**

High ratio of free straight sections

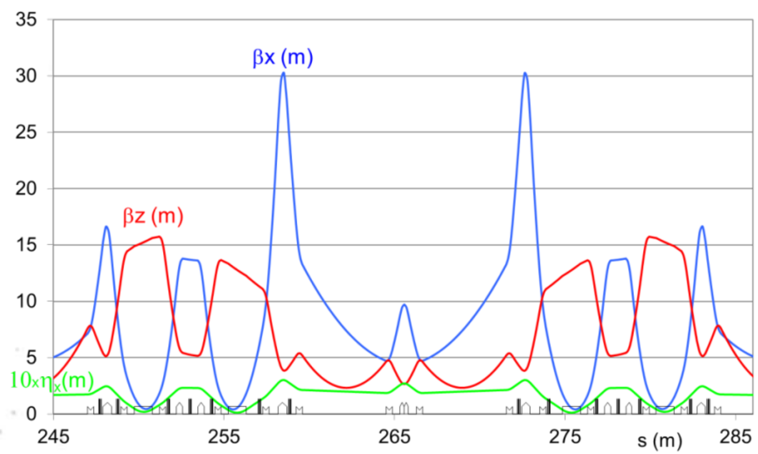
24 straight sections
4 x 12 m
12 x 7 m
8 x 3.6 m



Very compact magnetic structure

11 families of quadrupoles
11 families of sextupoles

No chromatic/harmonic sextupole



One long straight section (**SDL13**, accommodating 2 long beamlines) **has been modified.**

General Context

- Present Working point of SOLEIL has been optimized for many years
  - w/o IDs, it is very robust even with large tune variations
  - Performance are 16h for total lifetime at nominal current and 95% injection efficiency
  - Online optimization have shown that it is difficult to improve the lifetime without degradation of the injection efficiency.
  - Complex lattice with 11 families of sextupoles
- **Powerful analytical and numerical tools** have been developed over the years: systematic exploration of the parameter space but they are time consuming.

- **Question: how to ensure that the best solution is found for a given lattice?**

- **Multi-Objective Genetic Algorithms (MOGA)** [1] for this purpose, as a complementary tool:
  1. It seems suitable for complex magnetic lattice with a large number of quadrupole and sextupole magnets.
  2. It could and should allow us to explore in a finite time (typically some weeks) new solutions never explored before with other optimization methods.
  3. It has been applied in other storage rings with promising results [2].

[1] A. Konak, D. W. Coit, A. E. Smith. Multi-Objective Optimization using Genetic Algorithms: A tutorial, 2006.

[2] M. Borland, V. Sajaev, L. Emery, and A. Xiao. Multi-Objective Direct Optimization of Dynamic Aperture and Lifetime for Potential Upgrades of the Advanced Photon Source. Technical report APS LS-319, 2010. 37, 63.

Used Tracking Codes : ELEGANT and TRACY3

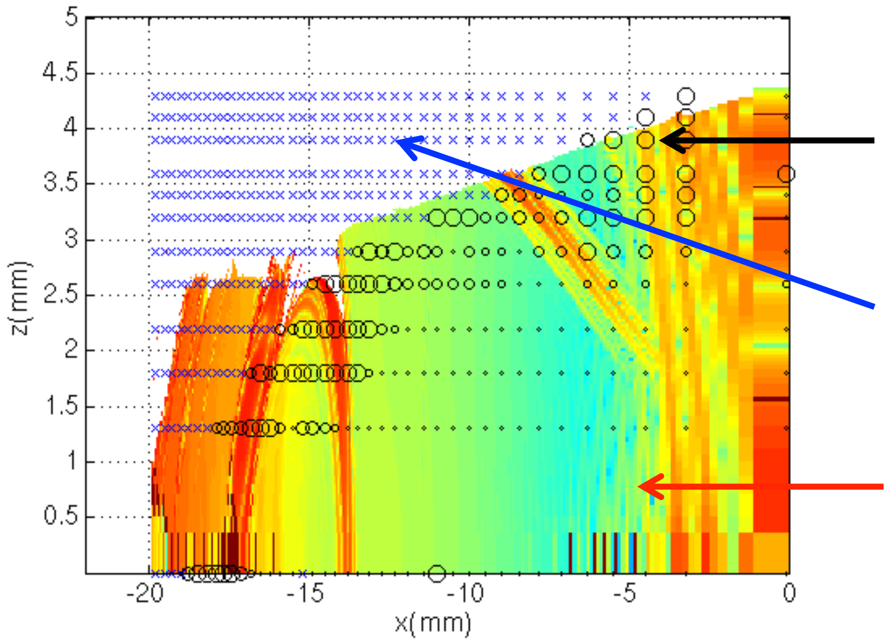
- It is the first time that ELEGANT was used at SOLEIL as a tracking code.

- TRACY3 has been used to check and refine the results obtained by ELEGANT.

- TRACY3 has been developed and tested experimentally at SOLEIL in order to validate the storage ring model.
  - **Predicted Tracy3 performance is very closed to experimental performance**

TRACY3: Simulation and Experimental Measurements at SOLEIL

On-momentum FMA : Bare machine



Black circles : partial beam losses for the measured one

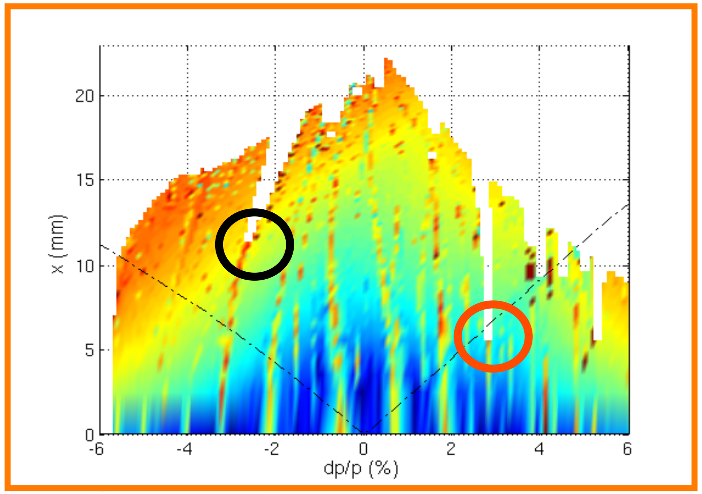
Blue crosses : total beam losses for the measured one

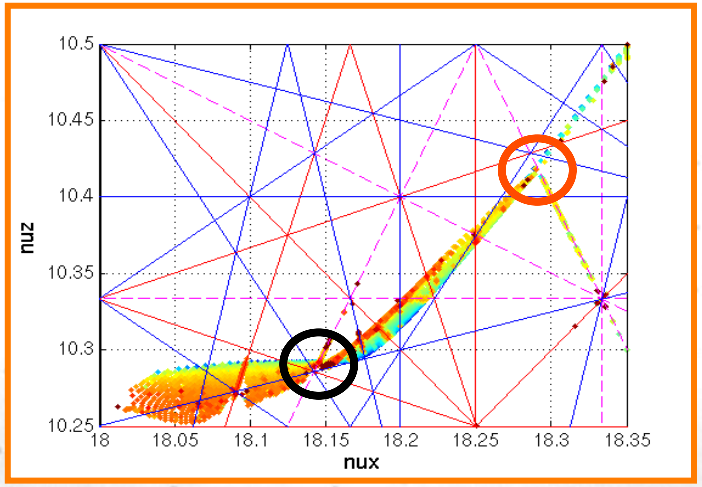
Colours for the simulated one

M.-A. Tordeux, P. Brunelle, A. Loulergue, A. Nadji and L. S. Nadolski. Linear and Nonlinear Model Opimization for SOLEIL Storage Ring. Proceeding of the PAC 09 conference, pp. 3931-3933.

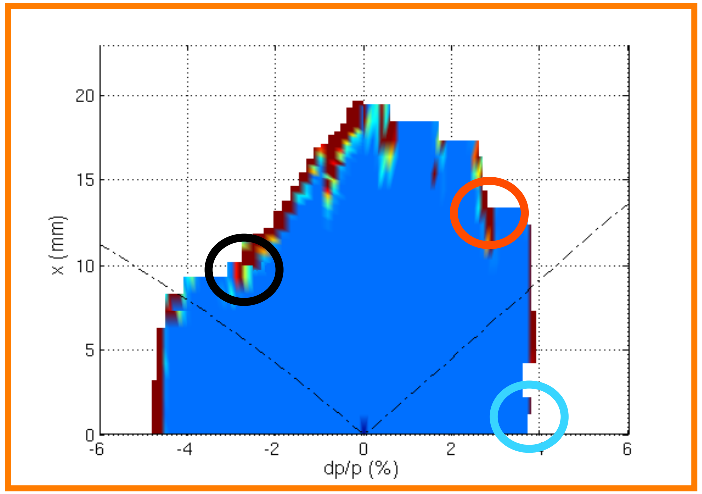
TRACY3: Simulation and Experimental Measurements at SOLEIL

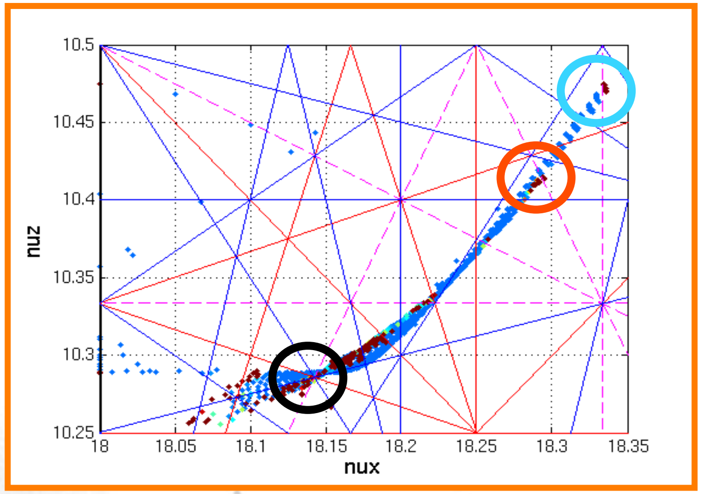
Simulations





Measurements





Off-momentum FMA : Bare machine

- (cyan circle) dp/p = + 4 % : $3\nu_x$=55.
- (orange circle) dp/p = + 3 % : $2\nu_x+\nu_z$=47
- (black circle) dp/p = - 3 % : $2\nu_x-\nu_z$=26

P. Brunelle, A. Loulergue, A. Nadji, L. S. Nadolski, M.-A. Tordeux. Nonlinear beam Dynamic Studies at SOLEIL using Experimental Frequency Map Analysis Proceeding of the IPAC10 conference, pp. 4653-4355.

Correcting the Dipole Edge Focusing in ELEGANT

- **Disagreement in the vertical chromaticity of 1.4.**
- The model of the dipole edge focusing [6] was defined as a **first order approximation** (second order not symplectic).

Parameter	TRACY3	Original ELEGANT version *	Original ELEGANT version #	Corrected ELEGANT version
(ξ_x, ξ_z)	(0.006, -0.035)	(-0.004, 1.405)	(0.006, -0,030)	(0.004, -0.071)

*[6] K. Brown. **A First (*)** and **Second (#)** Order Matrix Theory for the Design of Beam Transport Systems and Charged Particle Spectrometers. Internal report, SLAC-75, 1982*

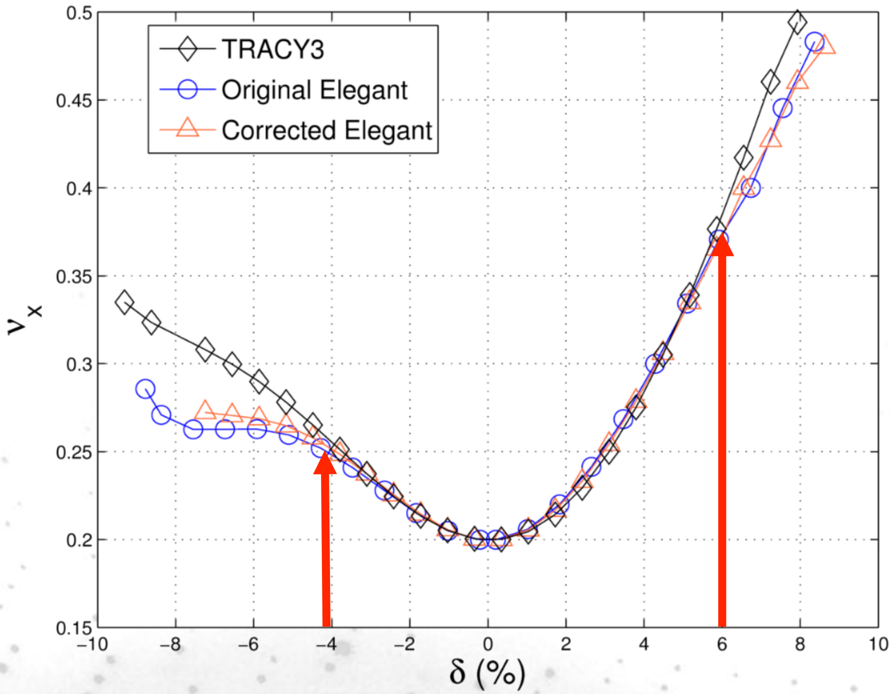
ELEGANT	Original version	Local version [7]
Vertical plane	$z' = z'_0 - \frac{1}{\rho(1+\delta)}\tan(\theta/_2 - \psi) z_0$	$z' = \frac{p_z}{(1+\delta)} = z'_0 - \frac{1}{\rho(1+\delta)^2}\tan(\theta/_2 - \psi)\, z_0$

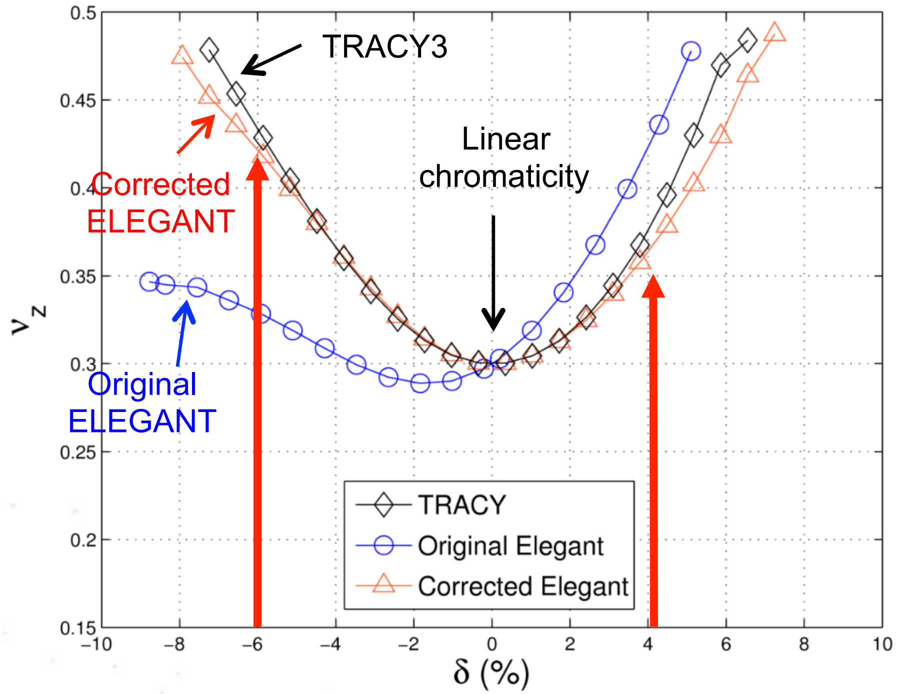
Comparison of the definitions of the dipole edge focusing before and after to the correction.

[7] (Bengtsson, 1994) J. Bengtsson and M. Meddahi. Modeling of Beam Dynamics and Comparison with Measurements for the Advanced Light Source. London, UK, 1994.

Long Term Tracking Comparison

- After the modification of the dipole edge focusing, the performance of the corrected version of ELEGANT is the same as TRACY3 for long term tracking in the range of [-6 %, 6 %] energy offset in the level of 10^{-2} tune error.





Dynamic Aperture Comparison Between ELEGANT and TRACY3

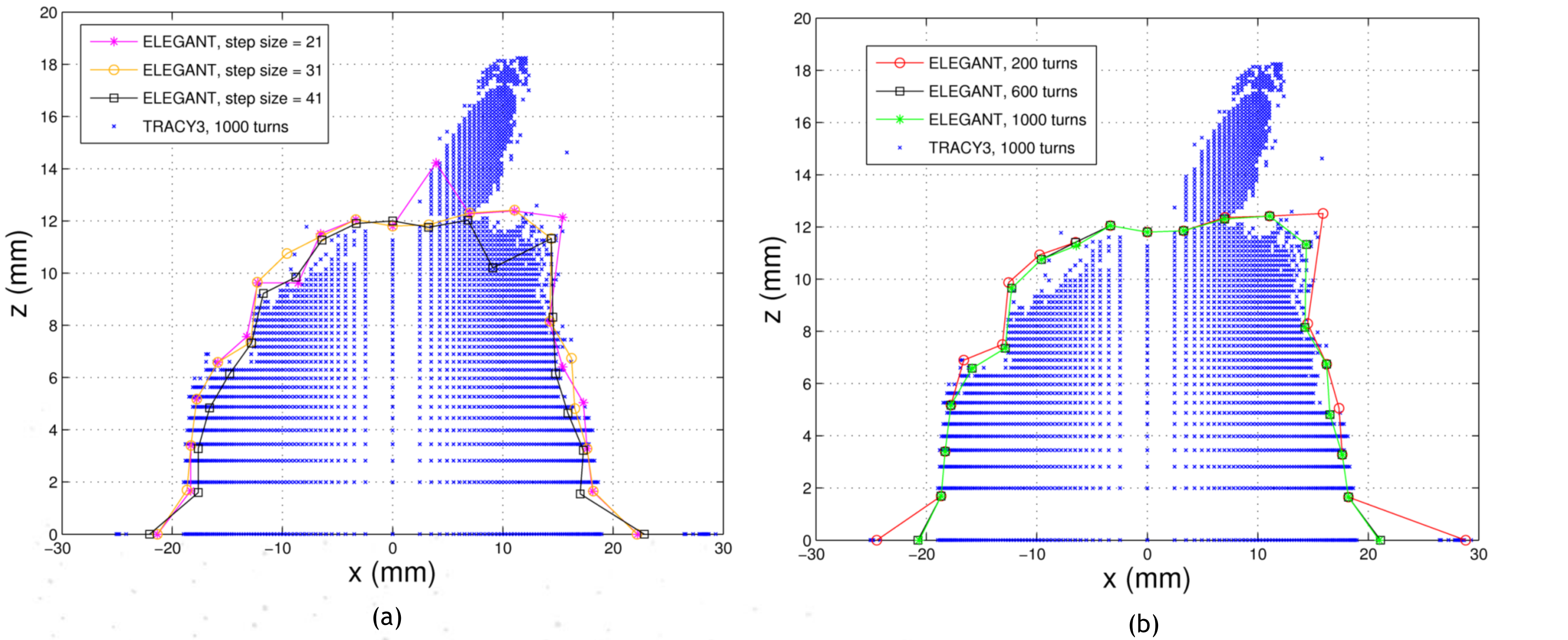
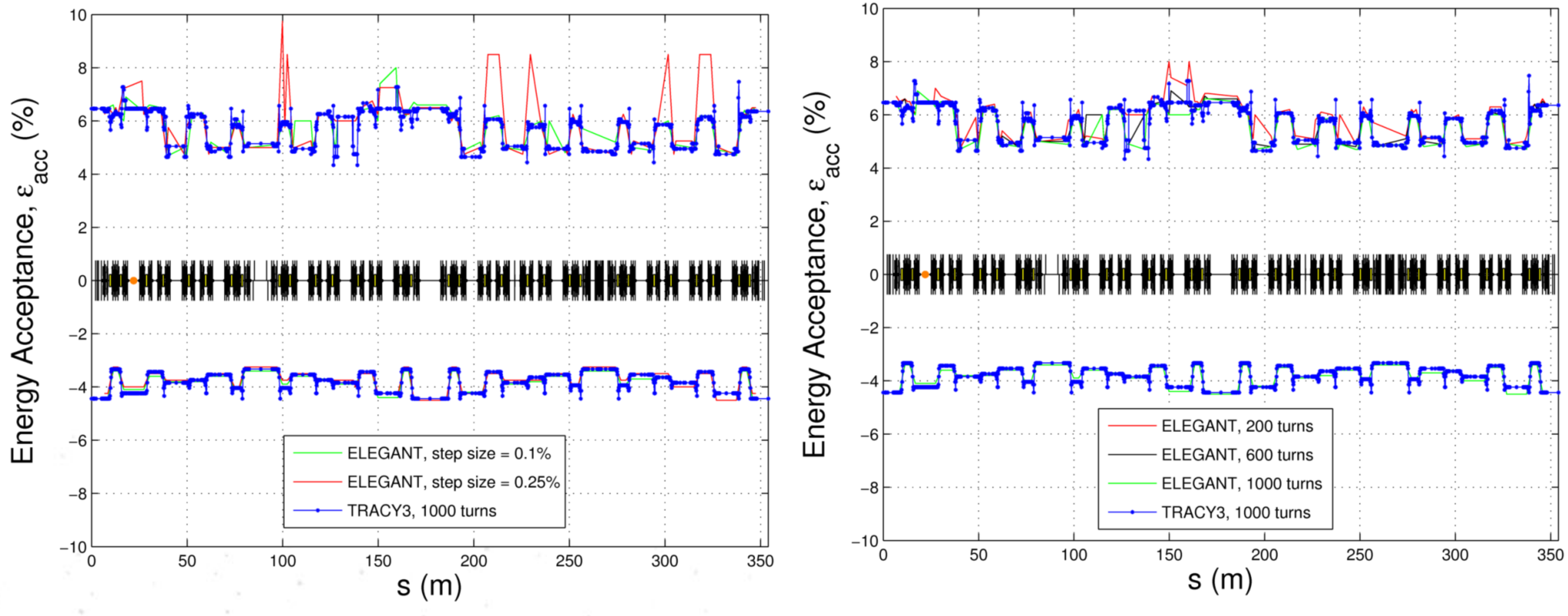


Figure 11: Comparison of the dynamic aperture of the SOLEIL2013 lattice calculated by TRACY3 with 1,000 turns (blue □)) and ELEGANT with 4D-tracking using parameters of Table 6 for different ELEGANT step sizes (a) and number of turns (b). a) The step sizes taken into account by ELEGANT are 21 (magenta *), 31 (orange o), 41 (black □) and 51 (green ∇) and the number of turn is 1,000.). b) The number of turns taken into account is 200 turns (red o), 600 turns (black □) and 1,000 turns (green *) and the step size is 31.

Momentum Aperture Comparison between ELEGANT and TRACY3:



(a) (b)

Figure 12: Comparison of the local momentum aperture of the SOLEIL2013 lattice calculated by TRACY3 and ELEGANT codes using 6D-tracking and a RF-voltage of 2.665 MV for different ELEGANT energy step sizes (a) and number of turns (b). In both figures the TRACY3 results (blue line) are computed with 1,000 turns and an energy step size of 0.1%. a) The ELEGANT steps size is 0.1 % (green line) and 0.25 % (red line) and the number of turns is 1,000. b) The number of turns used by ELEGANT is 200 turns (red line), 400 turns (black line) and 1,000 turns (green line) and the energy step size is 0.1 %. 6D-tracking parameters of Table 7.

MOGA SIMULATIONS

Genetic Algorithms and Accelerators: MOGA at SOLEIL

- The **Genetic Algorithms** has been applied in the last 20 years to optimize different parts of the accelerator complex.
- The version of Multi-Objective Genetic Algorithm (MOGA) used was created at the Advanced Photon Source 15 years ago [1] specifically for synchrotron light sources.

Starting Point: Nominal lattice of SOLEIL

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MOGA
- *Figures of merit*: Touschek lifetime and injection efficiency.
- *Objectives*: Momentum and dynamic apertures.
- *Variables*: Magnet sextupole strengths.
- *Constraints*: Same lattice configuration, limits in magnet strengths.

→

Pareto front: set of best solutions

→

Selection of new solutions with new magnet settings

[1] L. Emery. "Global Optimization of Damping Rings Designs Using a Multi-Objective Evolutionary Algorithm. Proceedings of the 2005 Particle Accelerator Conference, pp. 2962-2964, Knoxville, USA, 2005.

Simulated Results from MOGA

- Computation time: 1 month using 200 CPUs, 46,000 solutions.
- Adding the physical limitations of the SOLEIL vacuum chamber <u>but no insertion devices</u>
- Optimization variables: 2 quadrupole families (Q7 and Q9) for tune scanning and 11 sextupole families for nonlinear optimization.
- Chromaticities fitted to the operation values of 1.2 and 2.0.
- Touschek lifetimes computed by ELEGANT with 6 mm of bunch length, 1 mA of bunch current and 2.665 MV of RF-voltage for 1% coupling.

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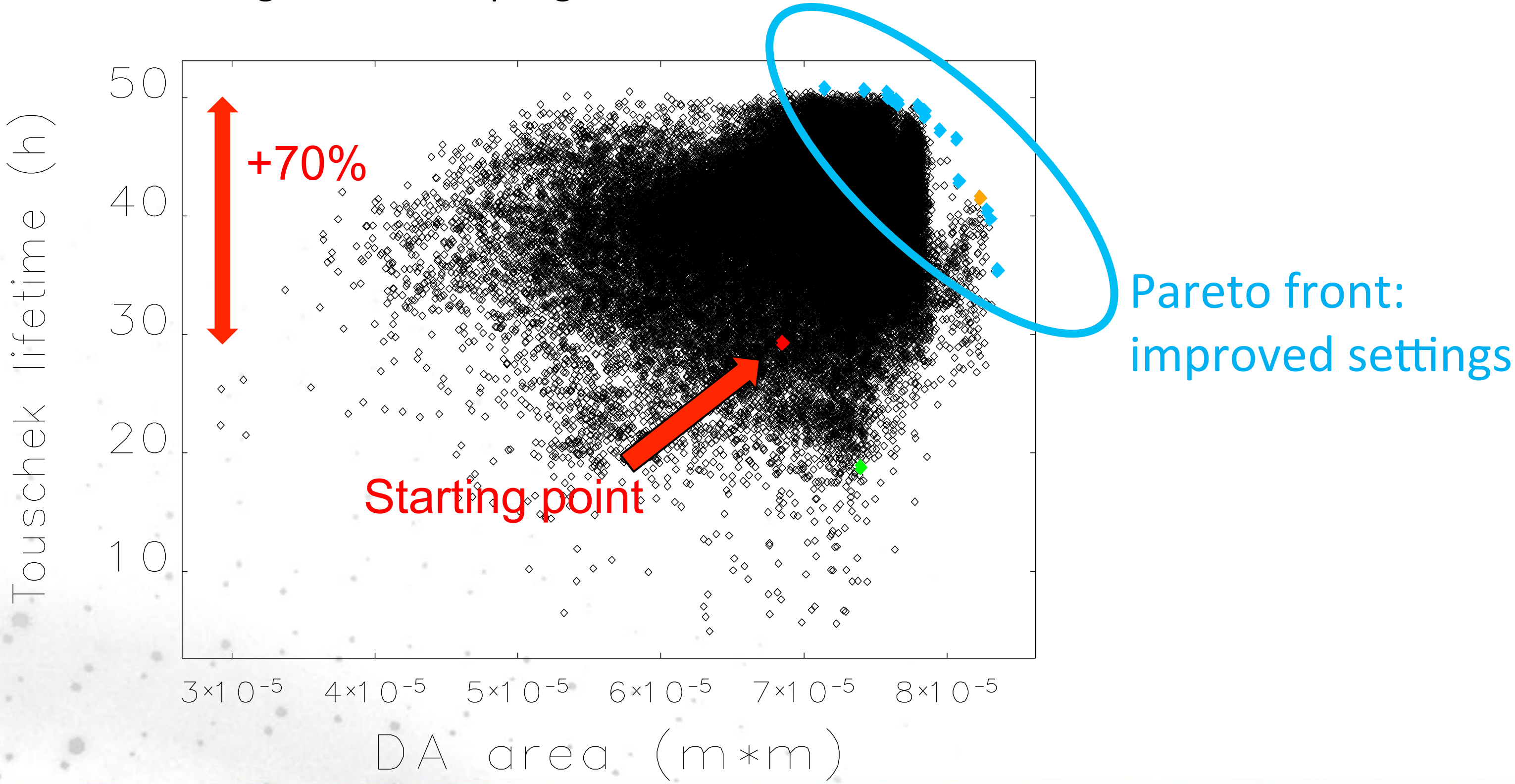
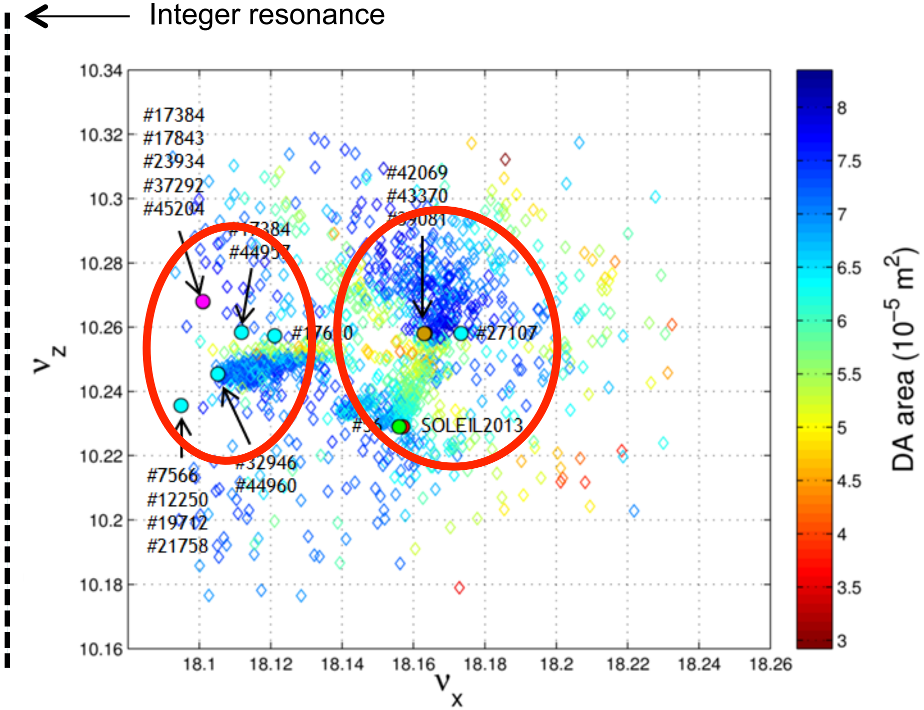
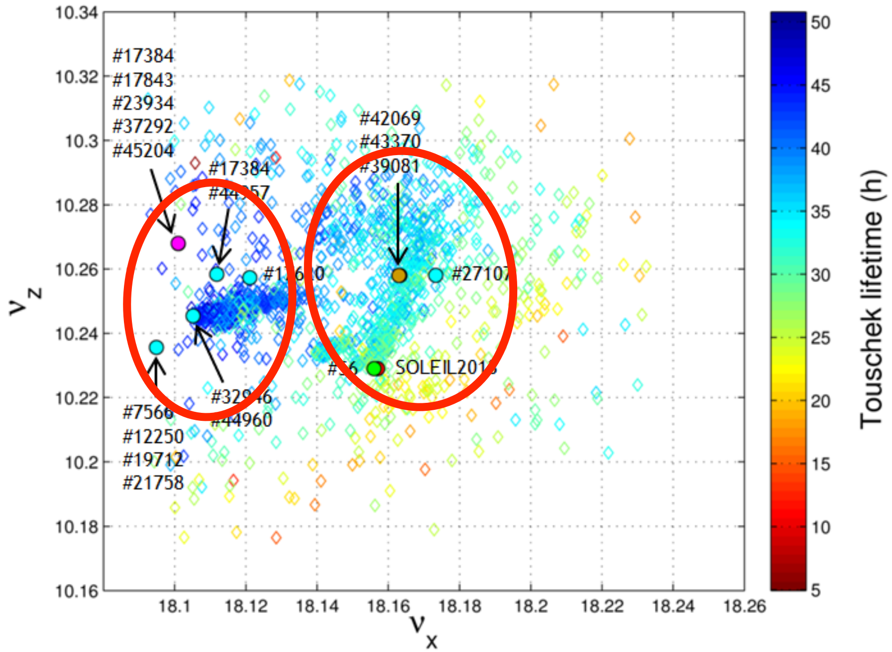


Tune Space Explored by MOGA

Integer resonance



Tune scan explored by MOGA color-coded with the area of the dynamic aperture



Tune scan explored by MOGA color-coded with the Touschek lifetime

- There are two groups: one around the nominal lattice (nux>18.14) and another one close to the integer resonance.

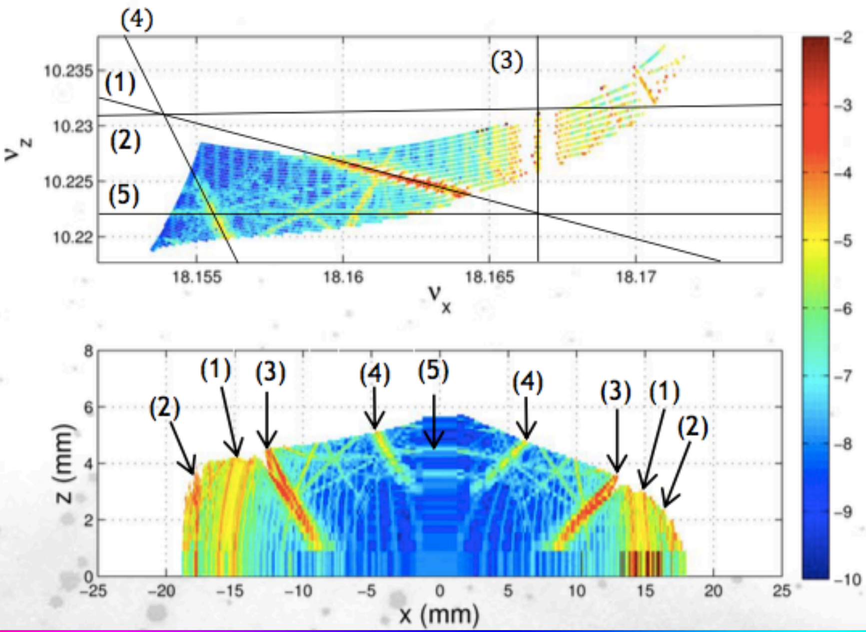
TRACY3: Frequency Map Analysis

- TRACY3 is used to:
  - Evaluate and select the Pareto solutions.
  - Add the multipole field components and the fringe fields in the model.
  - Analyse DA contents in terms of resonances with Frequency Map Analysis.

- The Frequency Map Analysis are based in the **diffusion rate** [7, 8] that allows to identify the resonance lines:

$$d = log_{10}\left(\sqrt{\left(\nu_x^{(2)} - \nu_x^{(1)}\right)^2 + \left(\nu_z^{(2)} - \nu_z^{(1)}\right)^2}\right)$$

(1): 1-1,000 turns
(2): 1,001-2,000 turns



FMA of the nominal lattice of SOLEIL calculated by TRACY3 code adding the vacuum chamber dimensions and the multipolar field components.

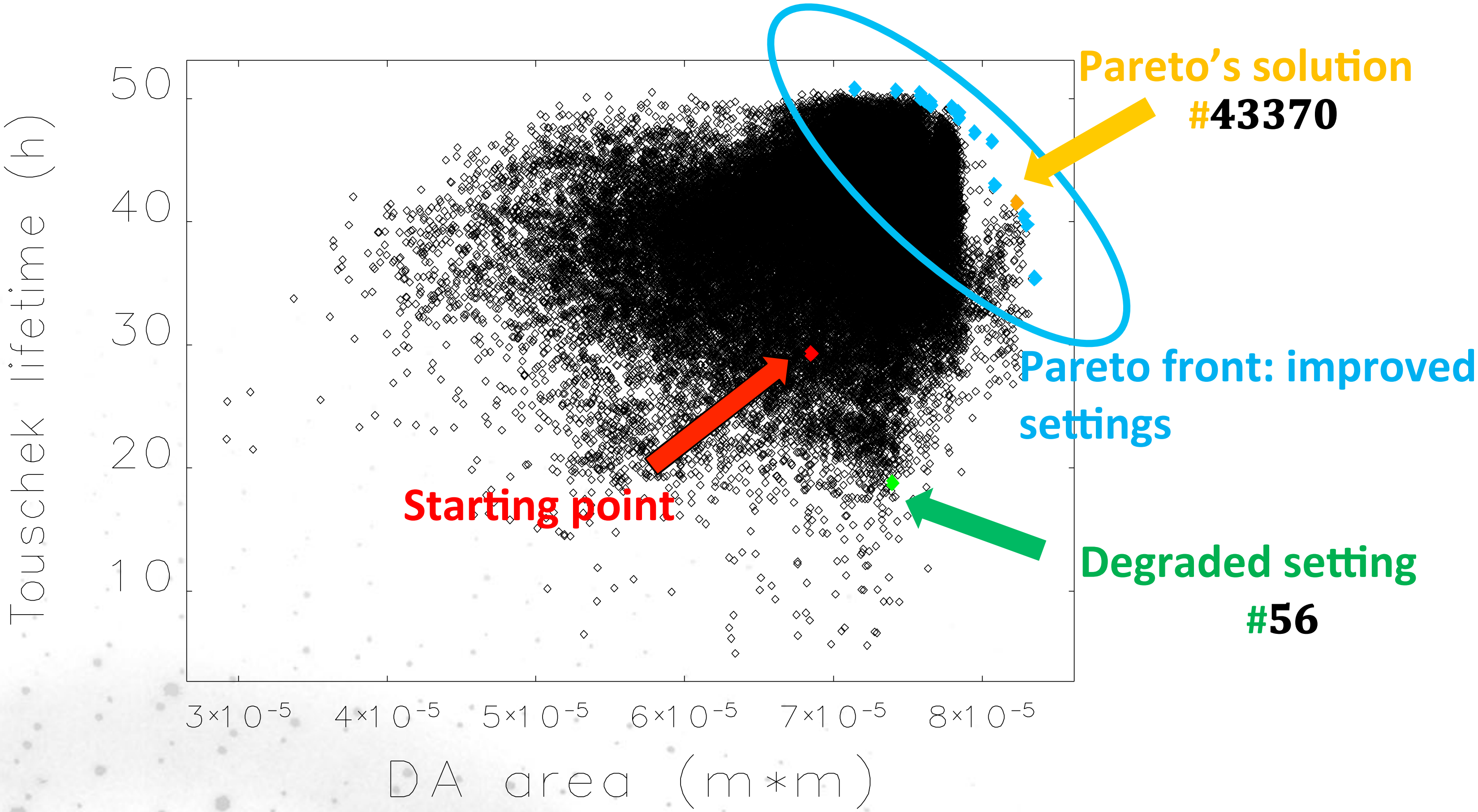
Resonance lines:

(1) $2\nu_x + 3\nu_z$=67,
(2) $\nu_x - 5\nu_z$=-33,
(3) $6\nu_x$=109,
(4) $5\nu_x + \nu_z$=101,
(5) $9\nu_z$ =92

[1] J. Laskar. Introduction to Frequency Map Analysis. Proceedings of 3DHAM95 NATO Advanced Institute, S'Agaro, June 1995, C. Simo Ed., pp 134-150.
[2] L. S. Nadolski. "Application de l'Analyse en Fréquence à L'Etude de la Dynamique des Sources de Lumière. PhD thesis, Paris Sud-Paris XI University, July 2001, 2001PA112120.

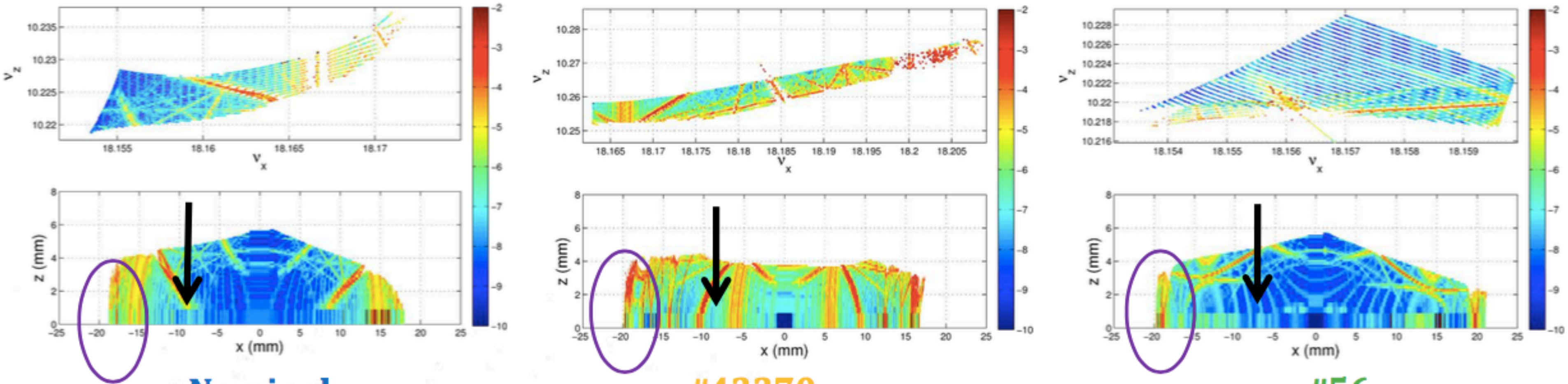
Selected Solutions for Beam-Based Experiments

- The optimized solutions #43370 (belonging to the Pareto-front) and #56 with degraded Touschek lifetime :



Selecting Solutions for Beam-Based Experiments: DA and Injection Efficiency

On-momentum dynamics



Nominal	#43370	#56
(ν_x, ν_z) = (18.163,10.258)	(ν_x, ν_z) = (18.163,10.258)	(ν_x, ν_z) = (18.156,10.229)

- For the two selected lattices the dynamic aperture is large enough for injection.

Touschek Lifetime Improvement

➢ The Touschek lifetime performance seen before with ELEGANT is confirmed by TRACY3 introducing the multipolar field components and fringe fields:

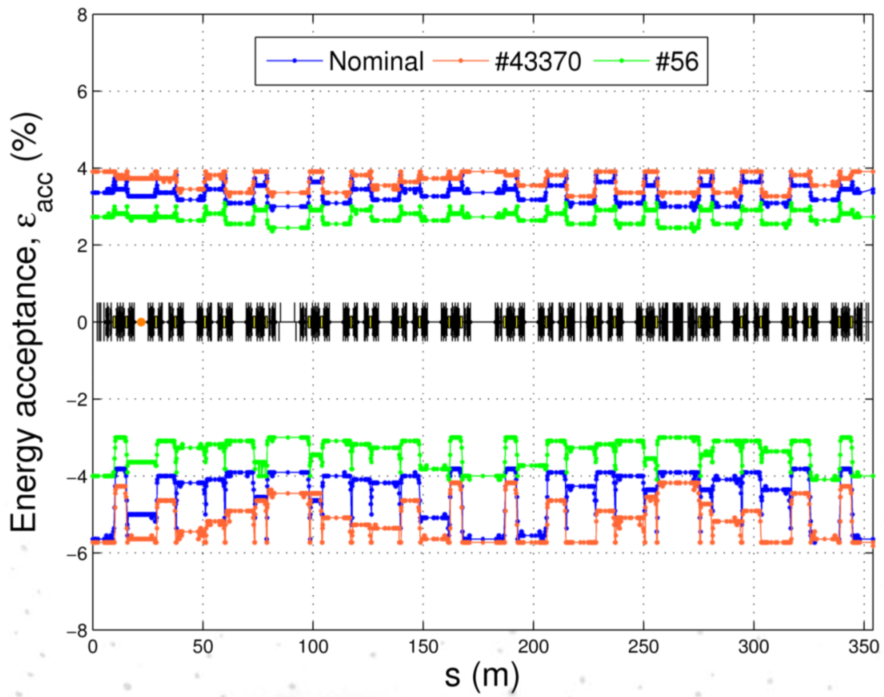
- Improvement of 33 % for solution #43370.
- Reduction of 49 % for the degraded solution of #56.

Lattice	Touschek Lifetime * (h)	
Nominal	35.3	
#43370	47.3	→ + 33 %
#56	18.1	→ - 49 %

(*) **taking into account the multipolar field components and fringe fields.**
Parameters used: 1 % of coupling, 3.87 nm·rad of horizontal emittance, 6 mm of bunch length.

Momentum Aperture and Tune Shifts with Energy

- The values of Touschek lifetimes of both solutions #43370 and #56 are explained in function of the energy acceptances.



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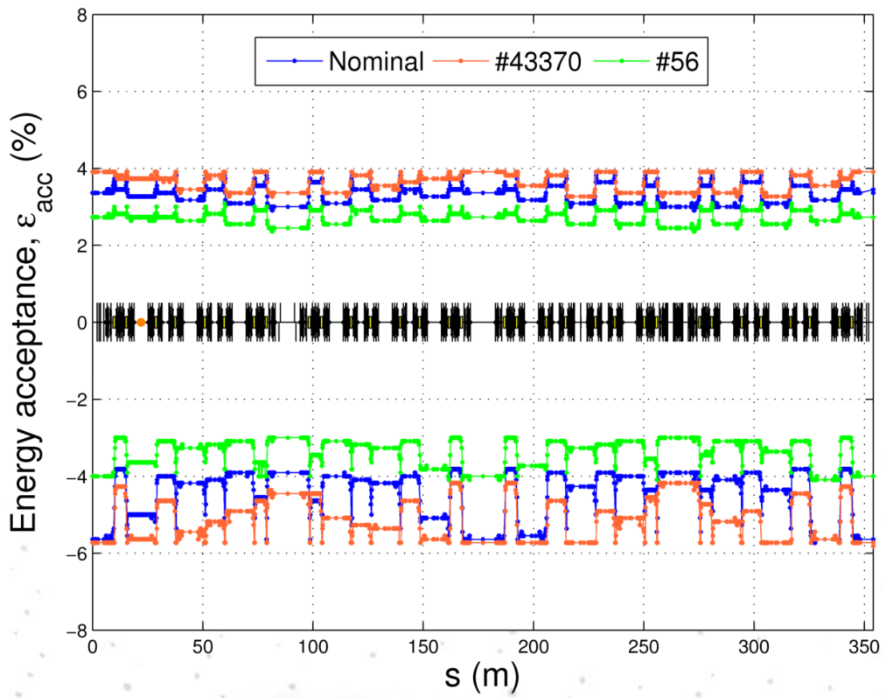

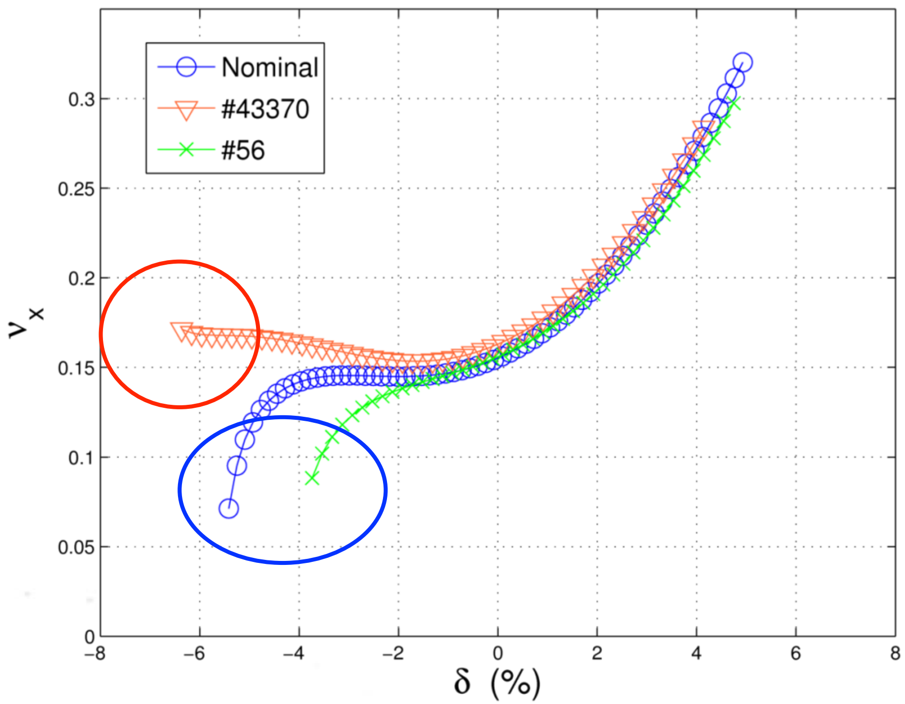

- MOGA is able to change very **high order chromaticity terms** to avoid the integer resonance line.

MOGA APPLICATION TO THE REAL MACHINE

Beam-Based Experiments

- **Goal: test the predictions made by MOGA.**

- Experimental conditions:
  - Insertion devices fully open (they are not taken into account in the simulations).
  - The same conditions of tunes and chromaticities.
  - Same physical aperture as in the simulation.
  - The bunch current is maximized and the total current is minimized to reduce the contribution of the gas scattering.

Machine Configuration			**Measured Beam Parameters**	
Parameters	Values		**Parameters**	Values
(MV)	2.7			1.2 ± 0.1
I (mA)	150			2.0 ± 0.1
Bunch Current (mA)	1.4		**(nm rad)**	4.18 ± 0.01
Number of bunches	104		**(pm rad)**	41 ± 0.1
P (mbar)	$3.0 \pm 0.1\ 10^{-10}$		**k (%)**	1.00

Beam Lifetime and Injection Efficiency Measurements

Lattice	ν_x	ν_z	τ^{SIM} (h)	τ^{MEAS} (h)	τ_{Tous}^{SIM} (h)	τ_{Tous}^{MEAS*} (h)	Injection Efficiency (%)
Nominal	18.155	10.229	**19.8**	**16.8** ± 0.5	**23.8**	**20.1** ± 0.7	**90**
#43370	18.163	10.258	**24.8**	**23.5** ± 0.5	**29.9**	**30.5** ± 0.8	**95**
#56	18.157	10.229	**11.1**	**9.7** ± 0.5	**12.2**	**10.7** ± 0.6	**95**

(*) Computation hypothesis: 102.4 h for the gas lifetime calculated in the same conditions

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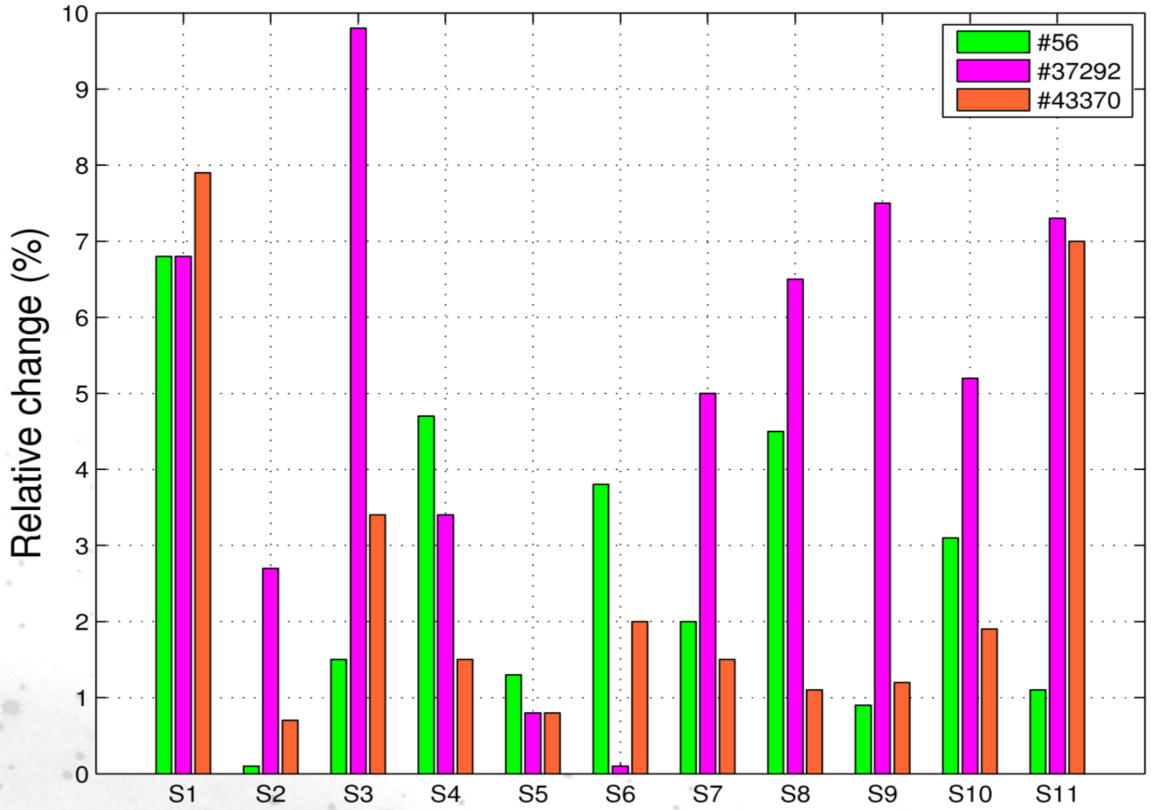
- The improvement of the total beam lifetime and Touschek lifetime (40-50 %) predicted by simulations **is confirmed by the experiments** as well as the decrease of the Touschek lifetime.
- **MOGA predictions have been validated by the experiments:**
  - Variation of sextupole quite significant
  - Beyond on-line otptimization turning knobs

Relative Changes of Sextupole Strength

The relative changes of sextupole strengths are as a maximum 10 %.



Conclusions

- **The optimization of the current lattice of SOLEIL using MOGA for the first time has been a <u>success</u>** giving an agreement between simulations and experimental results:
  - The improvement of 50 % of the Touschek lifetime is confirmed by the experiments without jeopardizing the injection rate.
  - Such an improvement was not expected before starting the study.
  - The maximum variation of sextupole strength is up to 10 % for some sextupoles.

- **These experimental results rely on an <u>accurate modeling of the lattice</u>:**
  - Including magnetic errors measured prior to the SOLEIL commissioning.
  - Including beam-based tuning using frequency map.
  - Including an accurate description of the physical aperture in the simulation code.
  - Including better understanding of the modeling of the beam lifetime and its various contribution.

X. Gavalda's PhD dissertation :

Multi-Objective Genetic based Algorithms and Experimental Beam Lifetime Studies for the Synchrotron SOLEIL Storage Ring
http://www.theses.fr/2016SACLS205