Multi-objective Dynamic Aperture Optimization for NSLS-II Ring

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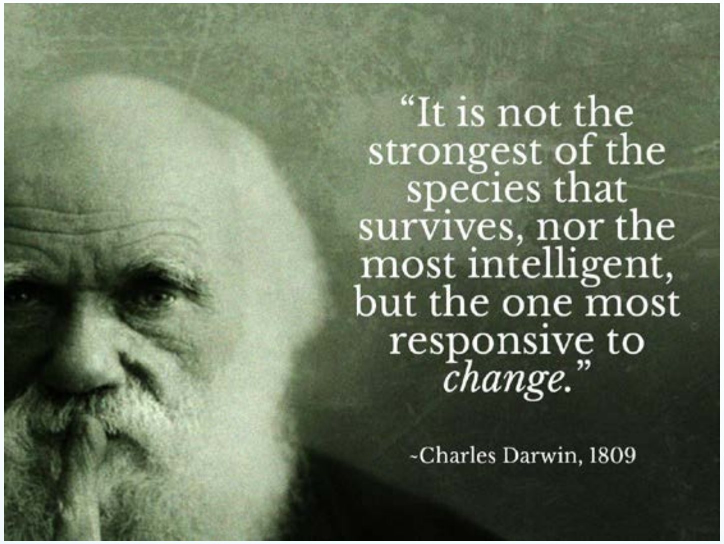
Outline

- Multi-objective genetic algorithm (MOGA)
- Existing optimizations on dynamic aperture
- New efficient method with MOGA
- Applications on NSLS-II storage ring
- Correlation between nonlinear driving terms and dynamic aperture

Genetic Algorithm (GA)

Genetic Algorithm (GA) mimics the evolution of nature:



物竟天擇
適者生存

Crossover: children inherit genetic codes from parents

Mutation: ***change*** the children's genetic information

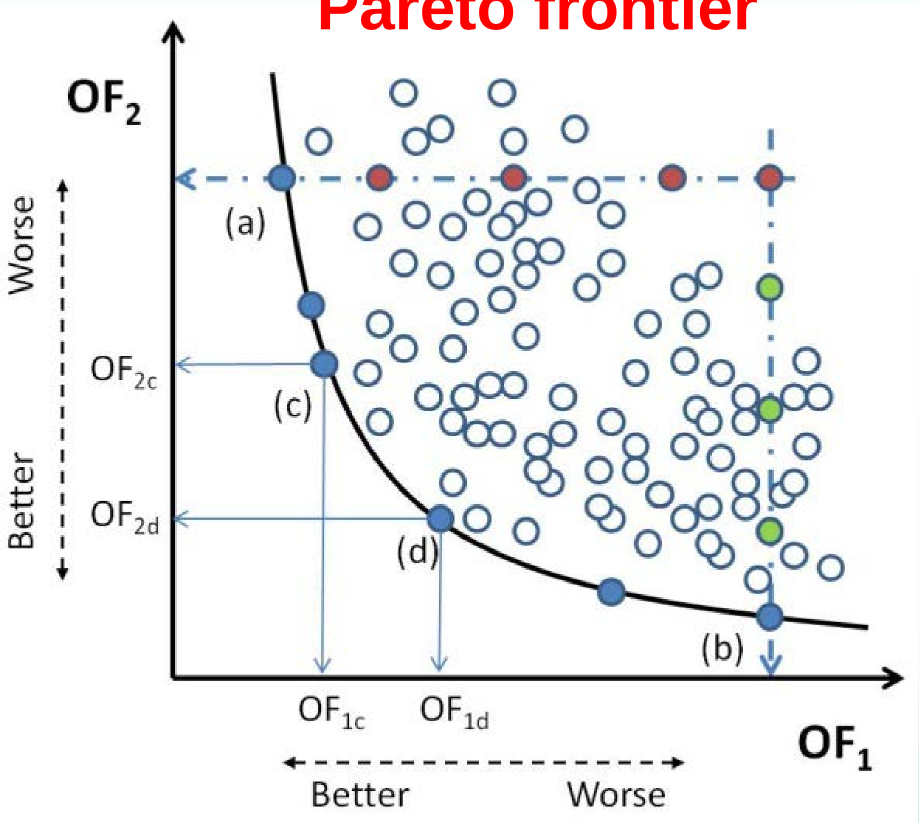
Selection: only these "**elites**" survive and reproduce

Multi-Objective Optimization

An example for two objectives ranking

Within a same rank, all candidates are equally good

Pareto frontier



Deb, Kalyanmoy - Natural selection: Non-dominated sorting in N-dimension space

Review of existing methods

- Method 1: minimizing the nonlinear driving terms with specific weights, i.e. MAD

Penalty function

Driving term

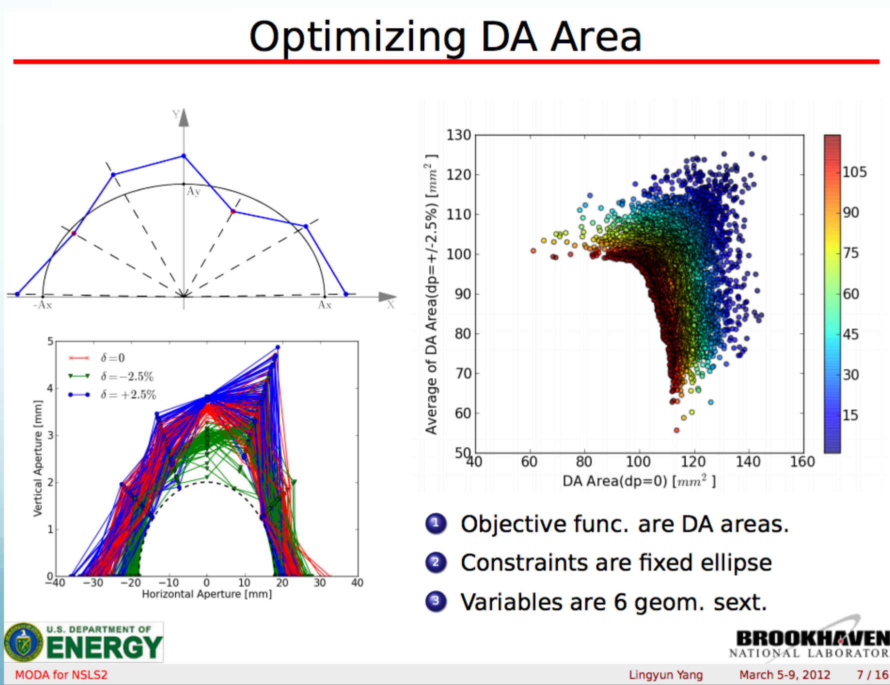
$$\sigma = \sum_i w_i h_i$$

Weight

- Difficulties:
  - Trapped in a local minimum
  - How to specify **weights**?

Review of existing methods

- Method 2: brute-force MOGA driven by direct tracking
  - L. Yang, Y. Li, et al. (PRST-AB, 2011)
  - M. Borland, integrated to ELEGANT

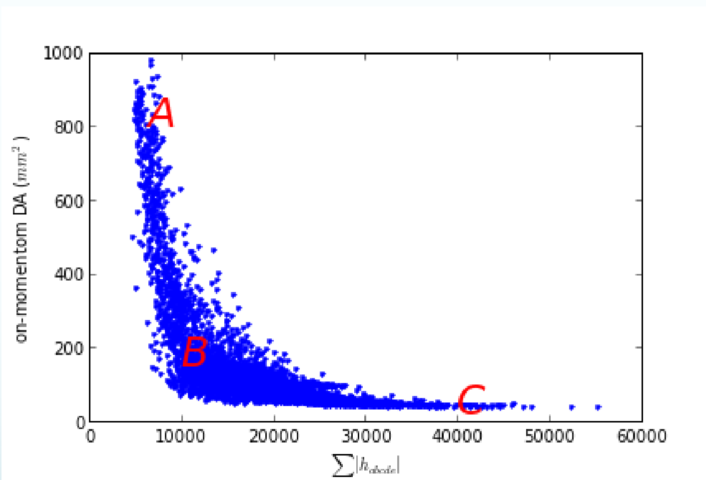


Works very successfully, but,
Difficulties:

- No physics is behind
- Very time-consuming in direct DA tracking, especially when your computer is not powerful, or your ring is big.

Motivation

- A strong correlation between DA and NDTs does exist .(L. Yang & Y. Li @BNL, M. Borland & L. Wang @ANL and SLAC)



Correlation of NDT and DA
Yang and Li, PRST-AB

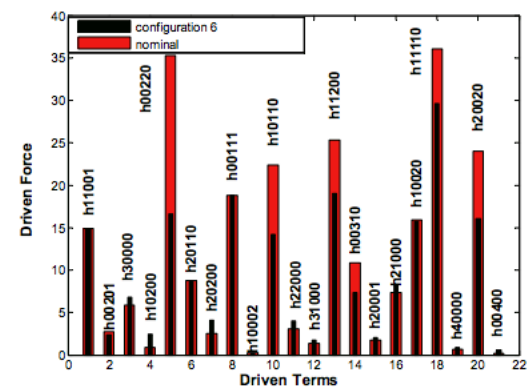


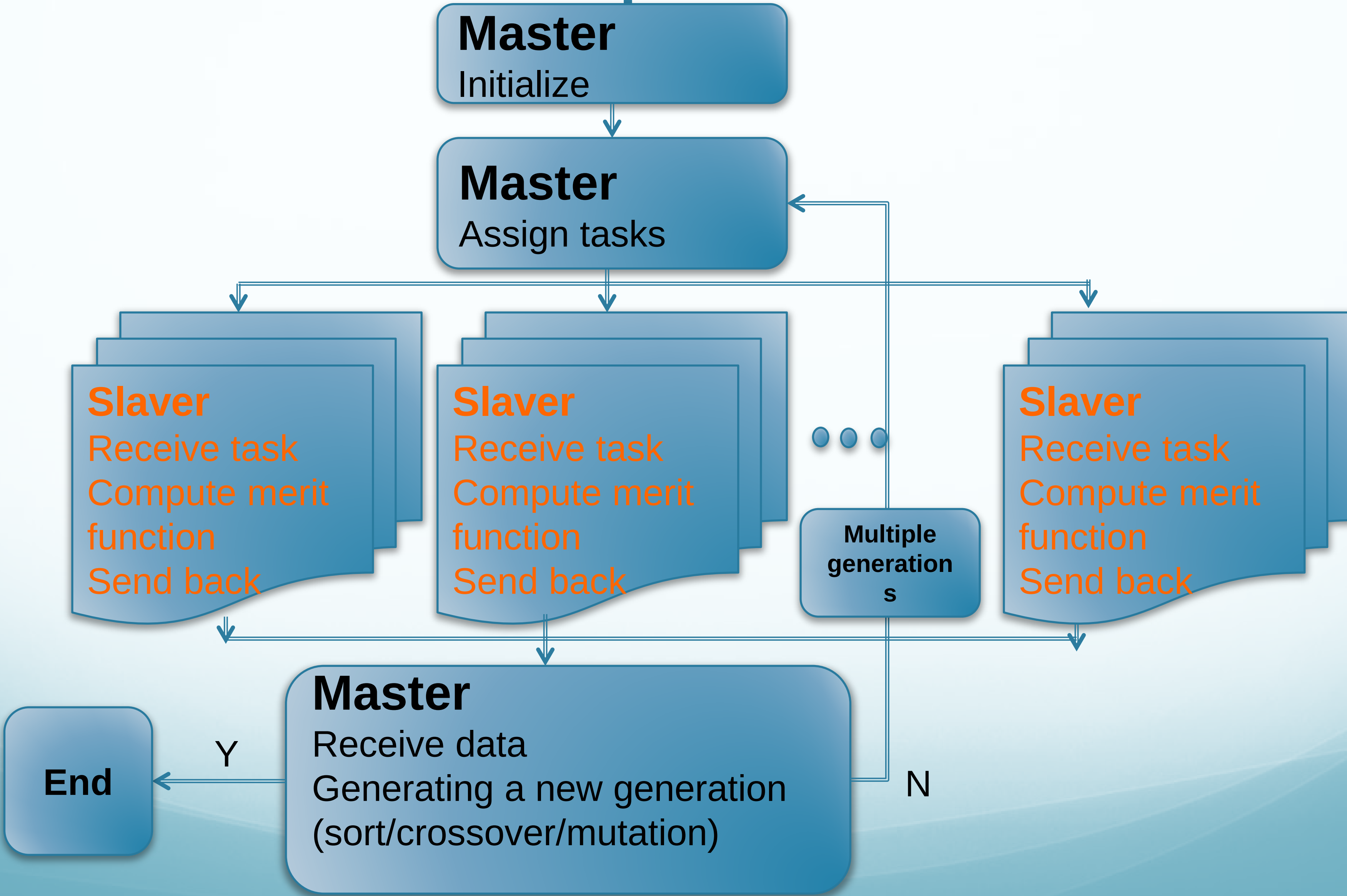
Figure 3. Automatic reduction of the driving terms after the optimization although DA is set as one of the objectives during the optimization.

M. Borland & L. Wang

An efficient method

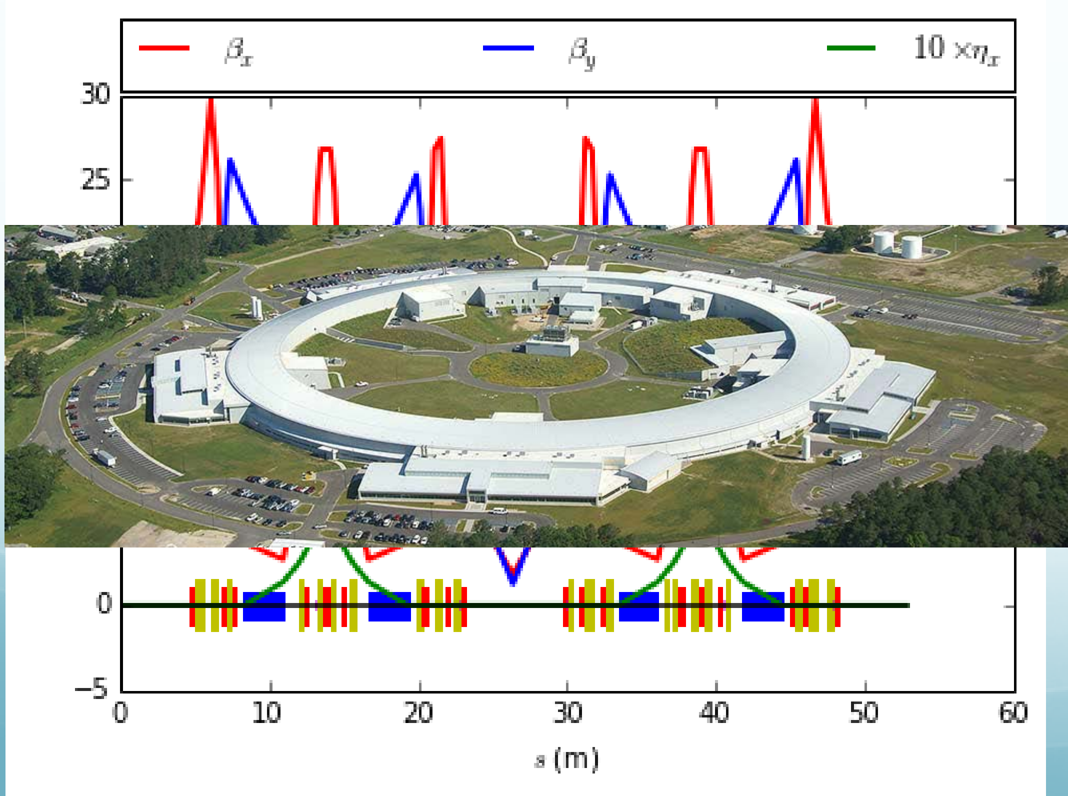
- **Using MOGA driven by NDT computing rather than DA tracking**
  - Be efficient: computing NDTs is much cheaper than DA tracking
  - Be of “physics”: having small low order NDTs is an necessary condition for larger DA

Parallel Computation and GA



Applications on NSLS-II ring

- Energy: 3GeV
- Emittance: 2nm bare, 1nm with 3x6.8m DWs
- Lattice: 30-standard DBAs (Chasman-Green)



Requirements for DA:

DA >= 15mm at high-beta straight for efficient injection

Energy acceptance >2.5% for sufficient beam lifetime

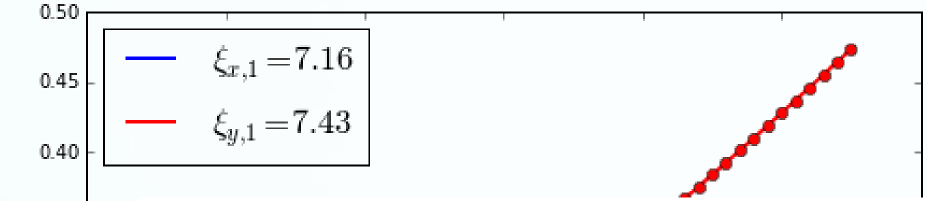
Tolerate numerous insertion devices and engineering errors

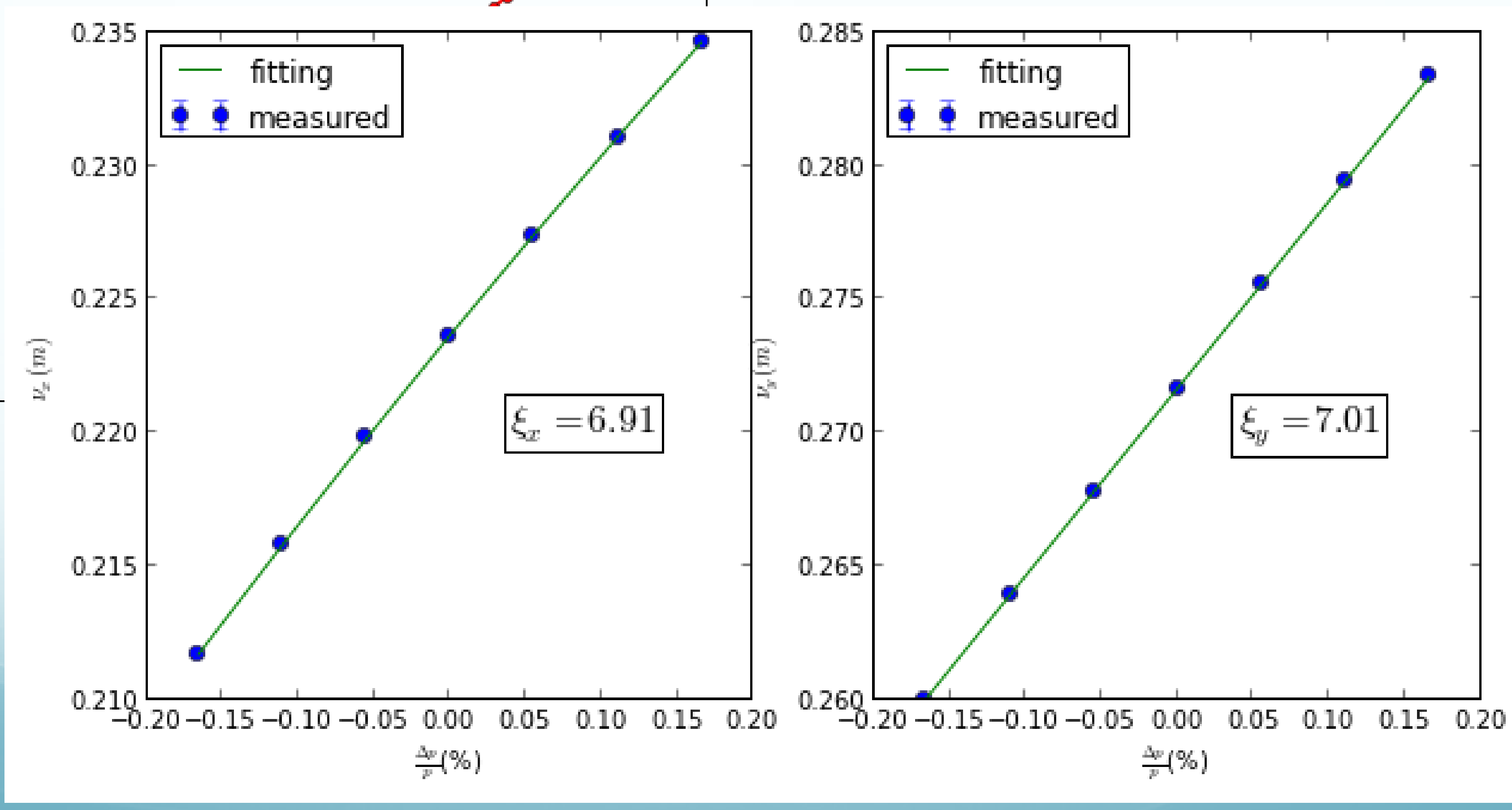
Simply case: Chromaticity +7/+7

- Purpose: high linear chromaticity to stabilize beam at high stored beam current
- Optimization procedure:
  - Tuning chromatic sextupoles to achieve +7/+7 linear chromaticity
  - Tuning 6 families geometrical sextupoles to optimize DA and energy acceptance
  - Penalty functions: first and second order driving terms: $h_{abcd,e}$, where a+b+c+d+e = 3 and 4 (totally ~ 30 terms)

$\xi_{x,y}$ = +7/+7 Dynamics: chromaticity

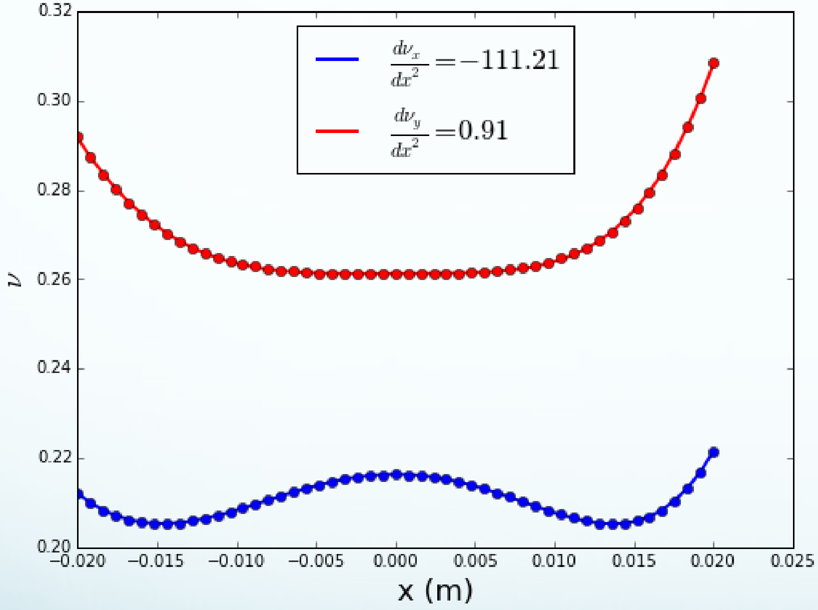
1. Linear chromaticity



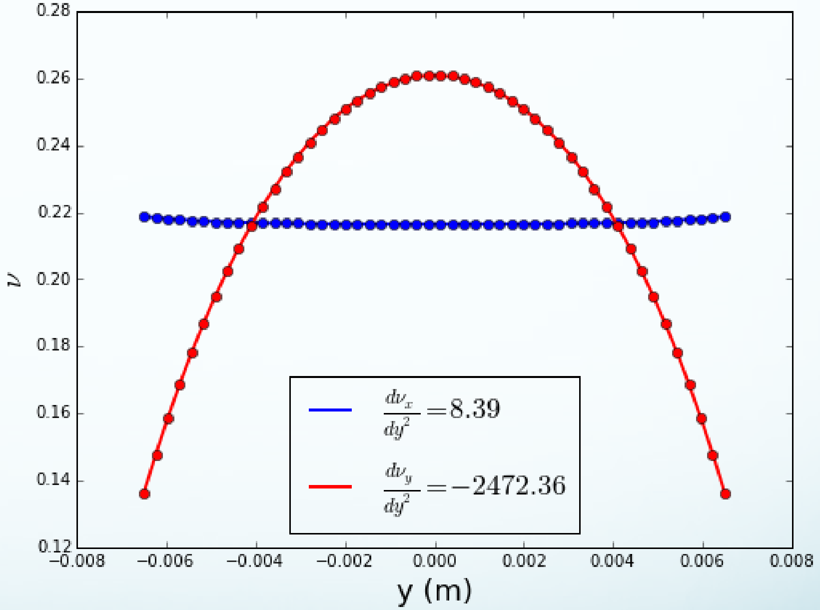


Tune dependence on amplitudes

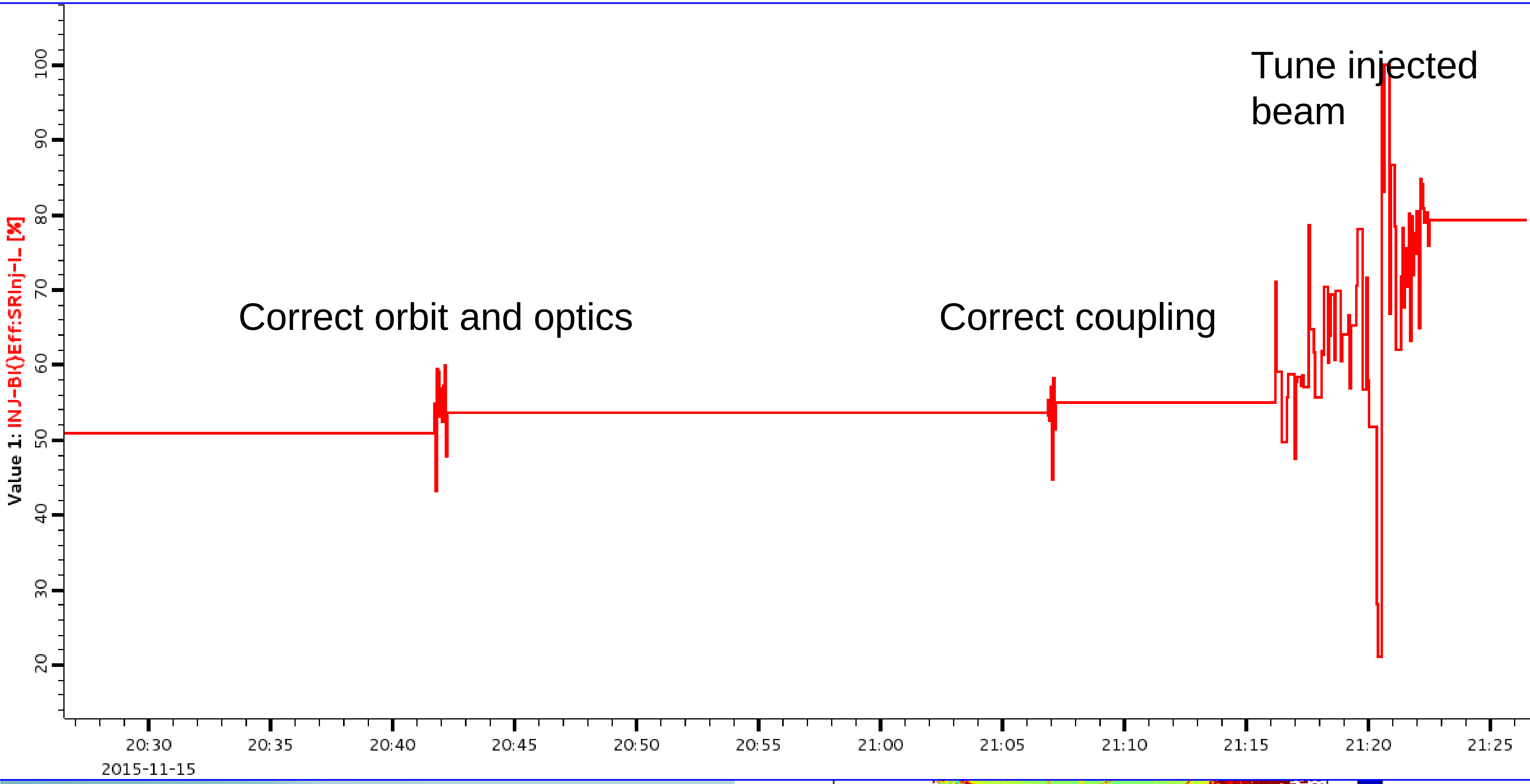
Horizontal

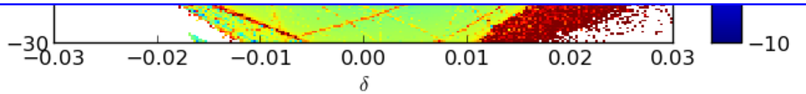


Vertical



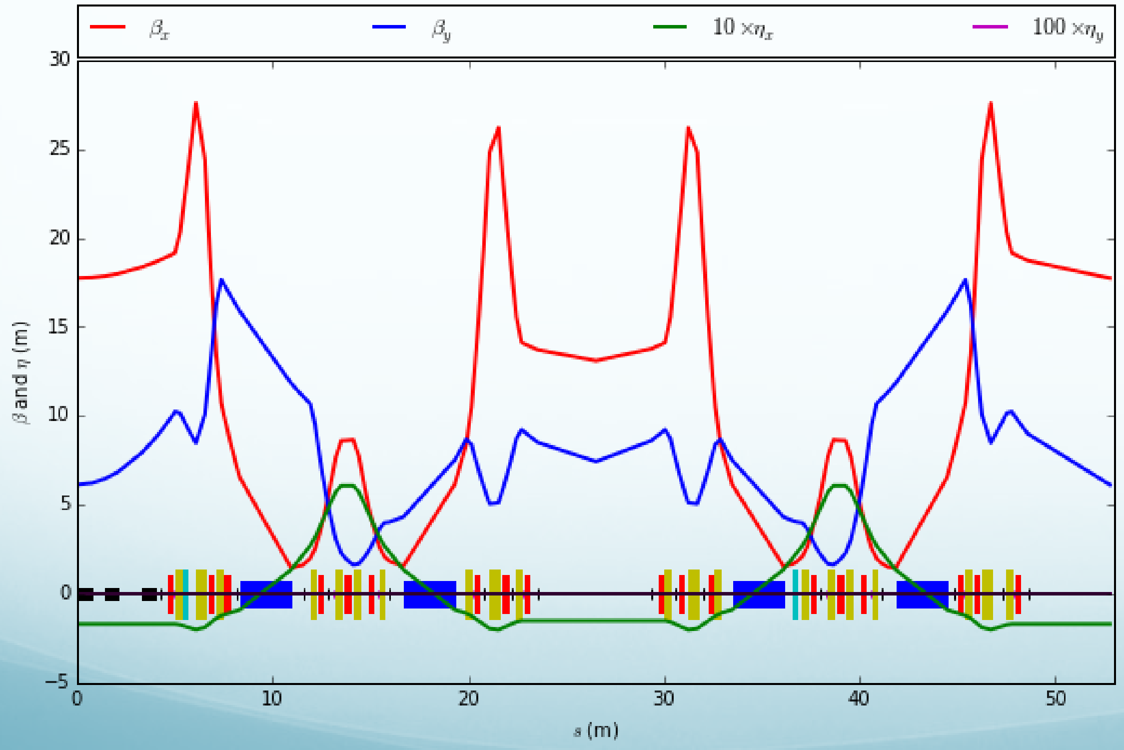
Dynamic aperture and energy acceptance





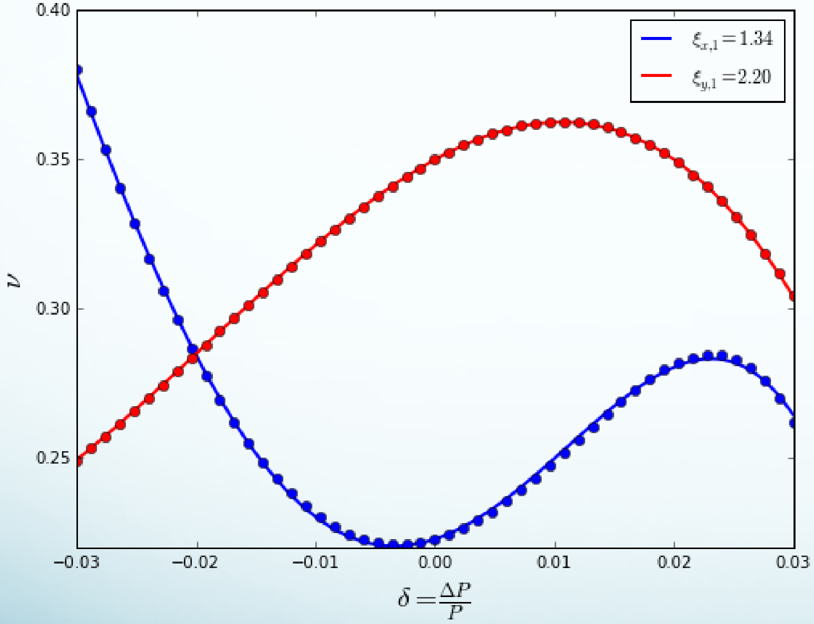
Demanding case: Low alpha Lattice

Purpose: to short bunch length by reducing momentum compactor from **5e-4** to **3.4e-06**



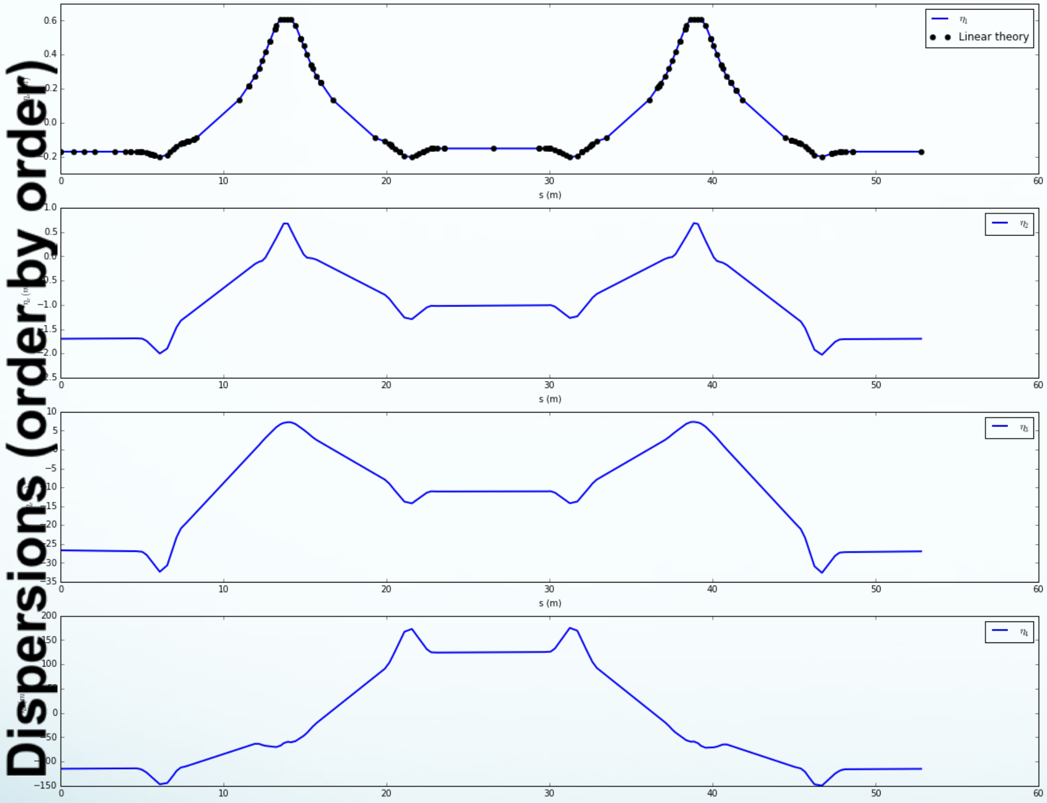
1. Linear chromaticity to +2/+2
2. Minimize higher order momentum compactions to have a stable longitudinal motion
3. Have sufficient DA and energy acceptance

Objective 1: chromaticity control



1. linear chromaticity close to +2/+2
2. Large high-order chromaticities

Objective 2: longitudinal stability

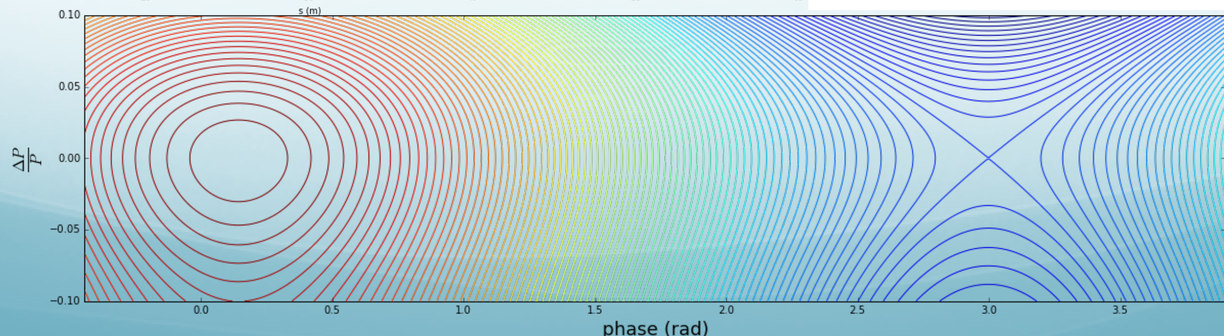


minimize higher order momentum compaction factors to have stable longitudinal motion

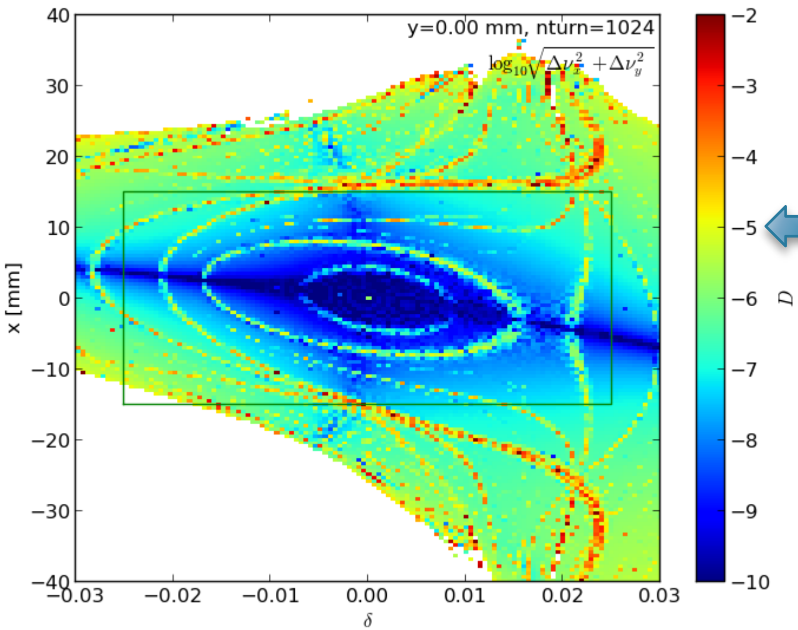
$$\alpha_1 = \frac{1}{\ell_0} \oint \frac{\eta_1(s)}{\rho} ds$$

$$\alpha_2 = \frac{1}{\ell_0} \int \frac{\eta_1{}'(s)^2}{2} + \frac{\eta_2(s)}{\rho} ds$$

$$\alpha_3 = \frac{1}{\ell_0} \int \eta_1{}'(s)\eta_2{}'(s) - \frac{\eta_1(s)\eta_1{}'(s)^2}{2\rho} + \frac{\eta_{3(s)}}{\rho} ds.$$

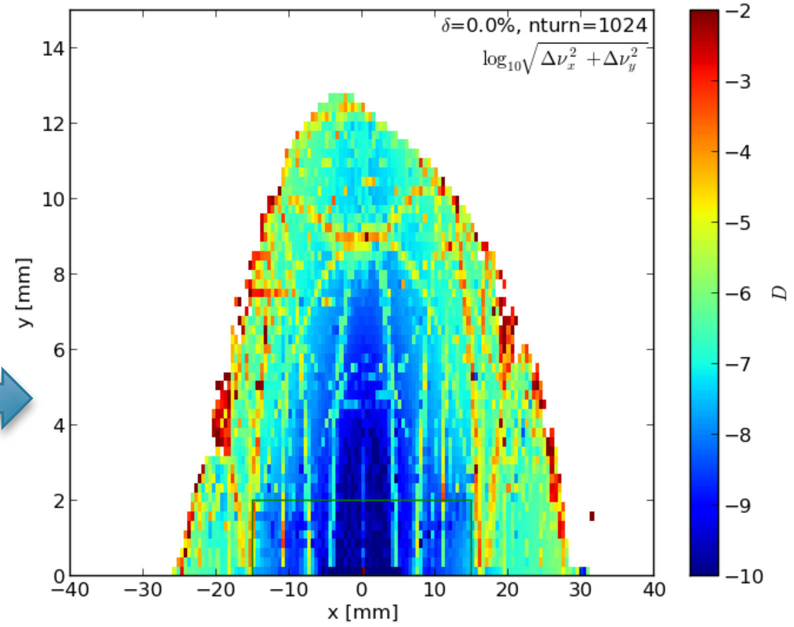


Objective 3: dynamic aperture and energy acceptance

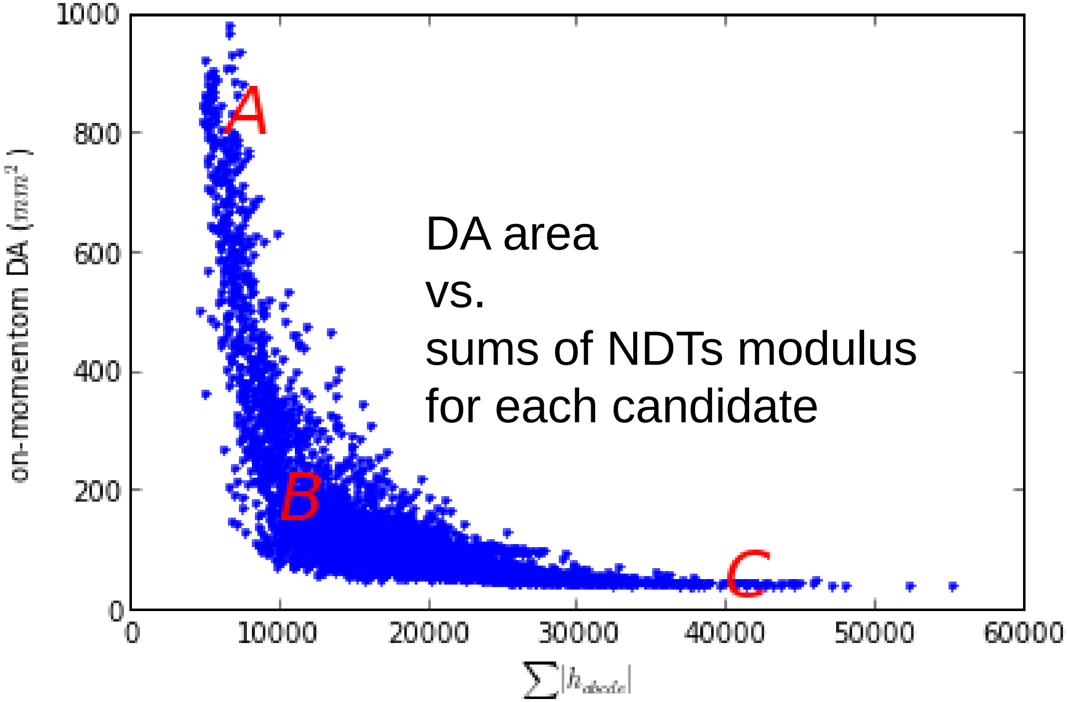


Sufficient energy acceptance for lifetime

Sufficient dynamic aperture for injection



Correlation between DAs and NDTs



A: small NDTs and large DAs

B: small NDTs but small DAs

C: large NDTs and small DAs

1. **Having small NDTs is an necessary but insufficient condition for having a large DA**
2. **Sufficient population per generation is the key parameter to get some good solutions**

New characterization with square matrix and sufficient conditions

We may now write this in the form

$$X = MX_0 \tag{2}$$

where to 4th order, we define the 14×1 monomial array

$$\tilde{X}_0 = (\, x_0 \quad p_0 \quad x_0^2 \quad x_0 p_0 \quad p_0^2 \quad \ldots \quad p_0^4 \,) \tag{3}$$

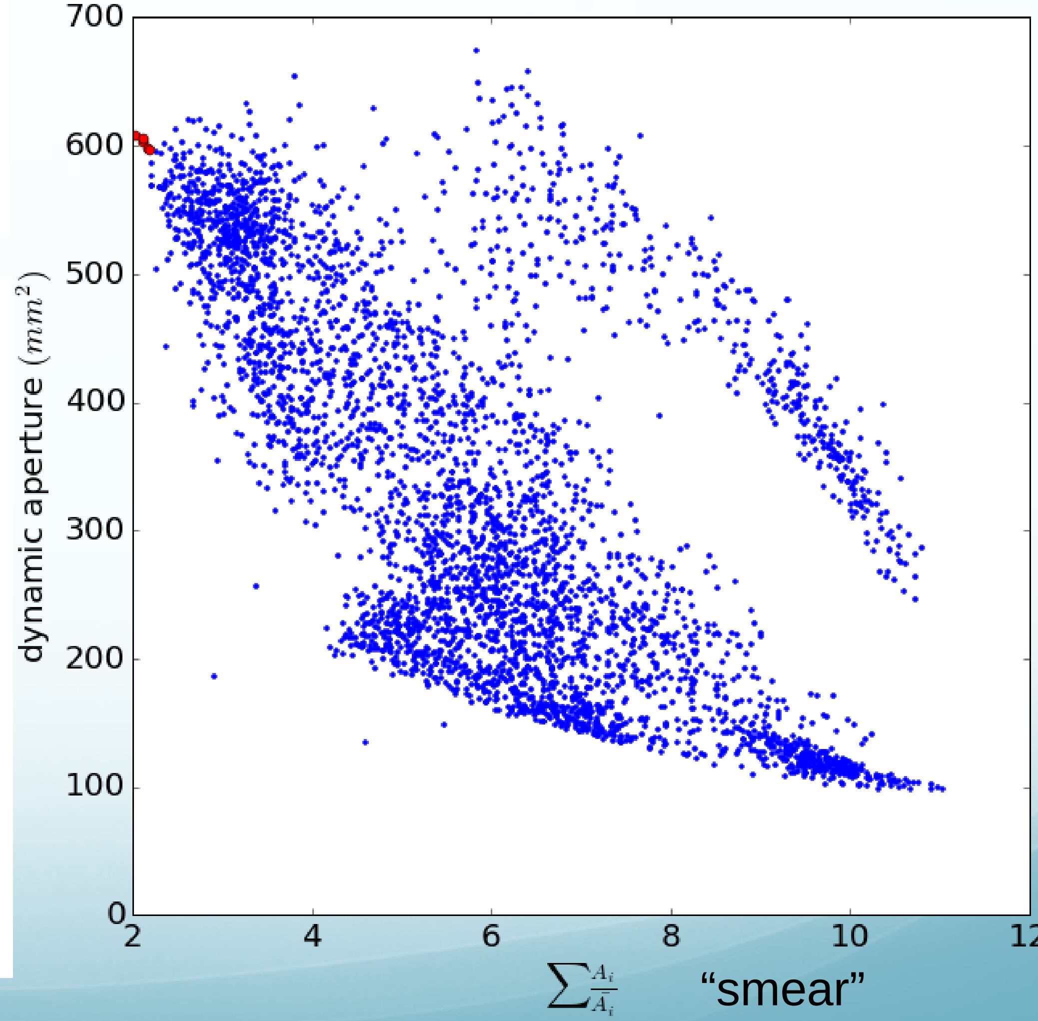
$$\tilde{N} = U\tilde{M}U^{-1} \tag{4}$$

$$= \begin{pmatrix} \tilde{N}_0 & & & & & \\ & \tilde{N}_1 & & & & \\ & & \tilde{N}_{-1} & & & \\ & & & \tilde{N}_2 & & \\ & & & & \tilde{N}_{-2} & \\ & & & & & \ldots \end{pmatrix} \tag{5}$$

$$\tilde{N}_k = e^{ik\mu} I + \tau^\dagger \tag{6}$$

with $k = \pm 1, \pm 2, \ldots$. I is the identity matrix and $\tau^\dagger$ the matrix with 1's just above the diagonal:

$$\tau^\dagger = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad \tau = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \tag{7}$$

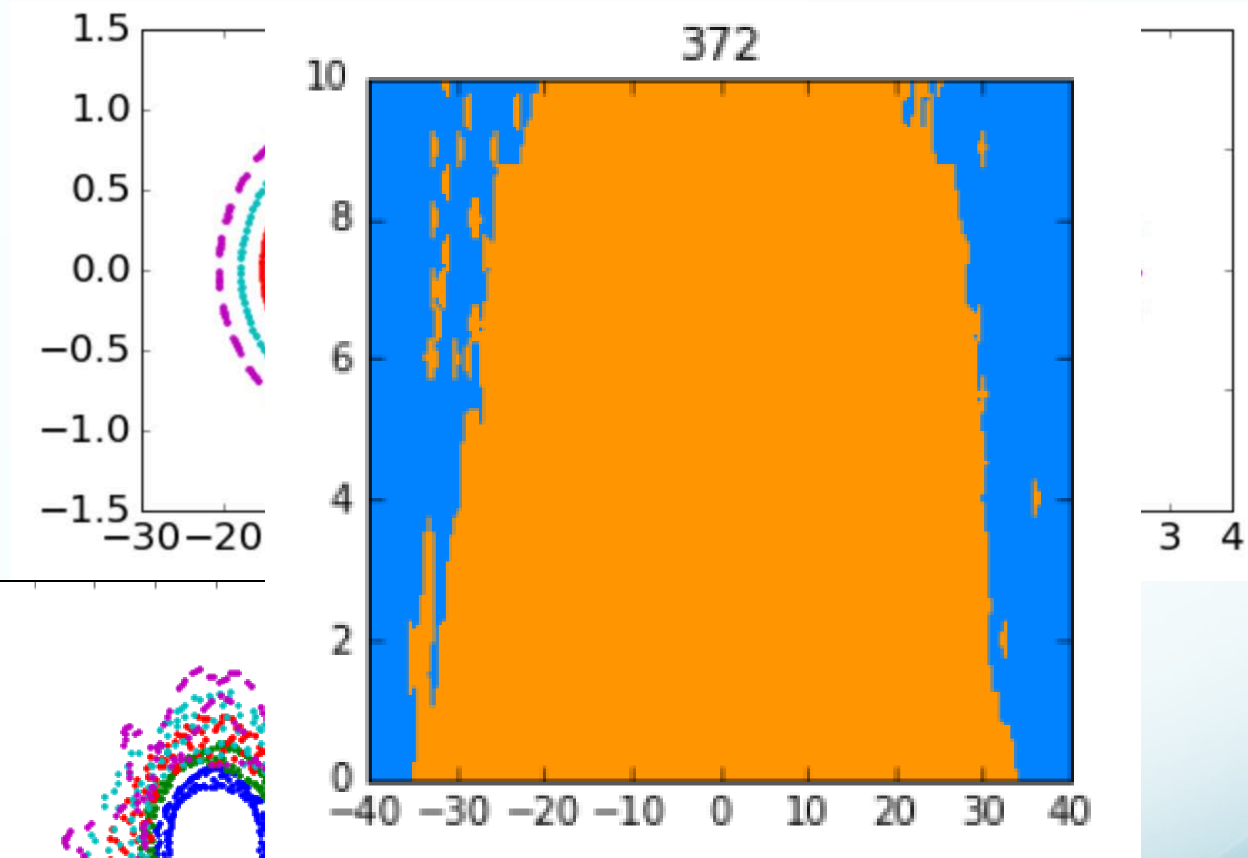


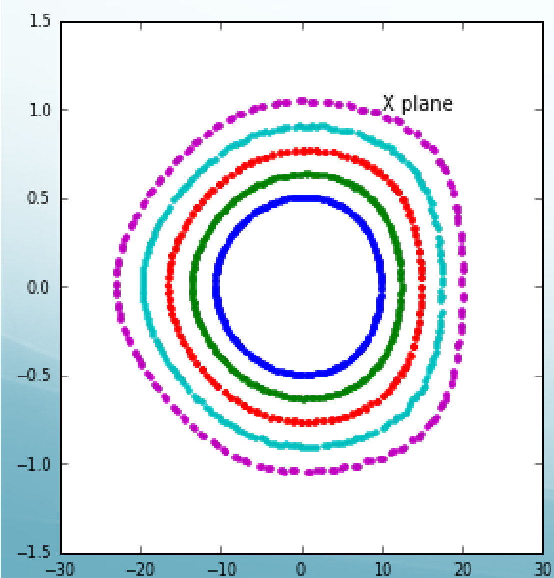
Li-Hua Yu

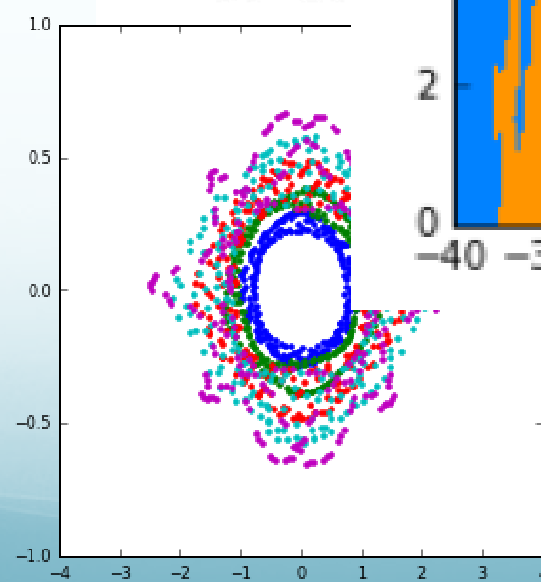
Phase space trajectories

Square matrix

Revisit ξ= +7/+7







Driving terms

Summary

- MOGA driven by the nonlinear driving terms is very **efficient**
- Having small low order NDTs is an **necessary**, but **insufficient** condition for have a decent DA.
- The number of populations is the key parameter. **Parallel** computation capability is preferable.
- Tracking simulation is the finial criteria to select the best solutions from the last generation
- New approach of characterization of nonlinear dynamics is under development