Efficient MOGA for NSLS-II Ring Dynamic Aperture Optimization

Yongjun Li, Lingyun Yang and Yoshi Hidaka
Photon Sciences Directorate, BNL

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Abbreviations

- GA: Genetic Algorithm
- MOGA: multi-objective genetic algorithm
- DA: dynamic aperture
- NDT: nonlinear driving term
- ID: insertion device
- DW: damping wiggler
- DBA: double bends achromat

Outline

- What is multi-objective genetic algorithm (MOGA)?
- Review of existing methods on dynamic aperture (DA) optimization
  - Minimization of nonlinear driving terms (NDT)
  - brute-force MOGA driven by DA tracking simulator
- Combination of existing methods creates a new efficient method
- Application on NSLS-II storage ring
  - Bare lattice
  - Insertion device integration
- Correlation between nonlinear driving terms and DA

What is GA and MOGA

Genetic Algorithm (GA) mimics the evolution of nature:

Crossover: generate children from parents.
Mutation: change the children.
Natural selection: keep only certain number of population.

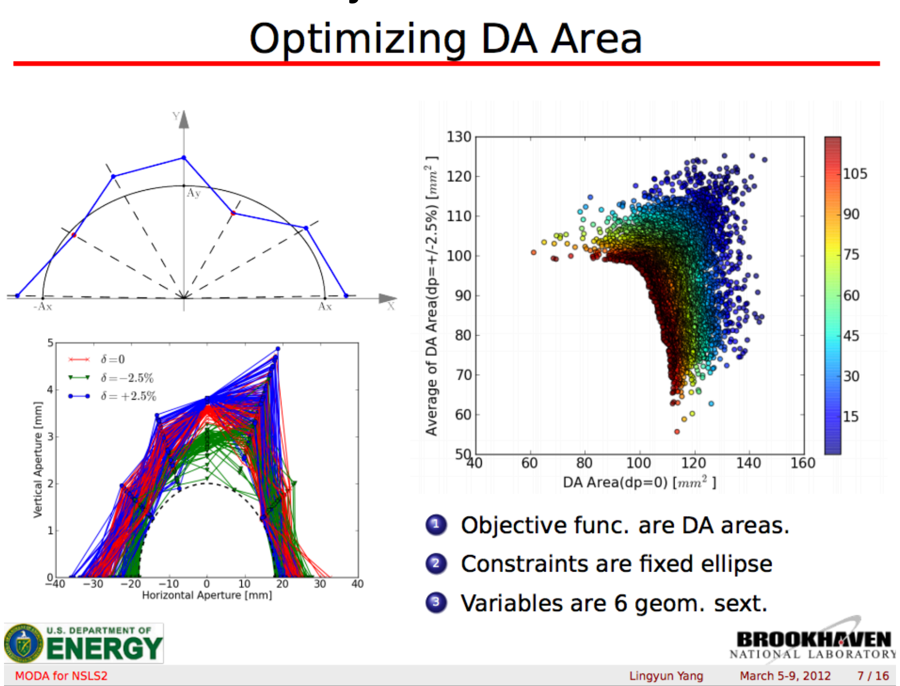
MOGA (Multi-Objective Genetic Algorithm)
1: Initialize population (first generation, random)
2: repeat (generation by generation)
  3: crossover: 2 parents generate 2 children.
  4: mutation: change children.
  5: calculate children's parameters **(parallel computation)**
  6: natural selection: "sorting" **(Non-dominated sorting)**
7: until stop(reach maximum generation, find solution, . . .)
8: a bunch of candidate solutions available, select the suitable solutions

Review of existing methods on DA optimization

- Conventional method: minimizing the nonlinear driving terms (NDT) with weights
  - NDTs can be calculated by
    - perturbation theory of Hamiltonian system
    - TPSA (non-symplectic)
    - Lie algebra (symplectic)
  - Difficulties of specifying optimization goal
    - There are numerous NDTs. Which ones are dominating DA?
    - If only single penalty function is used, how to specify weight to each NDT (**difficulty of weighting was mentioned by M. Ehrlichman for the SLS upgrade**).
    - **Multi-objective optimization is suitable for this case.**

Continued

- brute-force MOGA driven by tracking simulator have been implemented by
  - L. Yang, Y. Li, et al. (PRST-AB, 2011)
    - Objectives: on-, and off-momentum dynamic apertures
  - M. Borland, integrated to ELEGANT
    - Objectives: on-momentum DA and Touschek lifetime

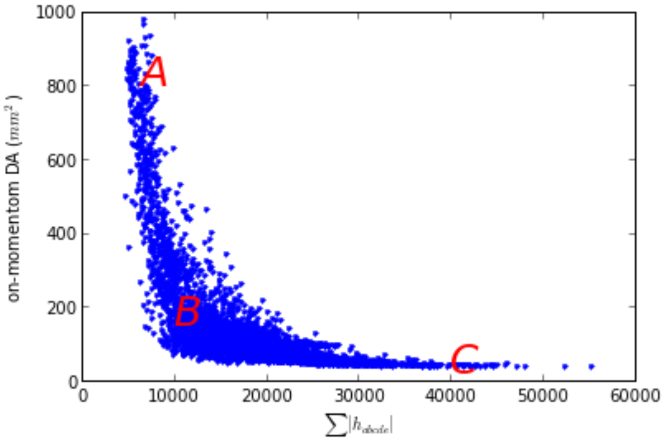


Difficulties of the brute-force MOGA:

- No physics is behind
- Very time-consuming in implement direct DA tracking (especially when your computer is not powerful)
- **Difficulty was mentioned by R. Bartolini – several weeks for one run**

Combination of existing methods creates a new efficient method

- We found that a strong correlation between DA and NDTs does exist .(L. Yang & Y. Li, M. Borland & L. Wang)



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

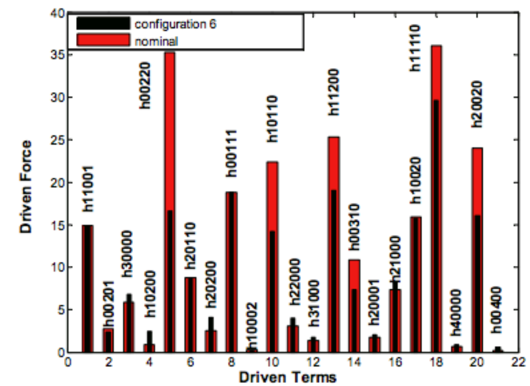


Figure 3. Automatic reduction of the driving terms after the optimization although DA is set as one of the objectives during the optimization.

M. Borland & L. Wang

continued

- New method: **using MOGA to optimize the NDTs rather than to implement DA tracking**
  - Be efficient: calculation NDTs is much cheaper than DA tracking
  - Be of "physics": having small low order NDTs is an necessary condition for larger DA
    - Both geometric and chromatic NDTs needs to be minimized simultaneously (Y. Cai's talk).
    - Some critical terms (tune with amplitude, nonlinear chromaticity) can be controlled as optimization constraints

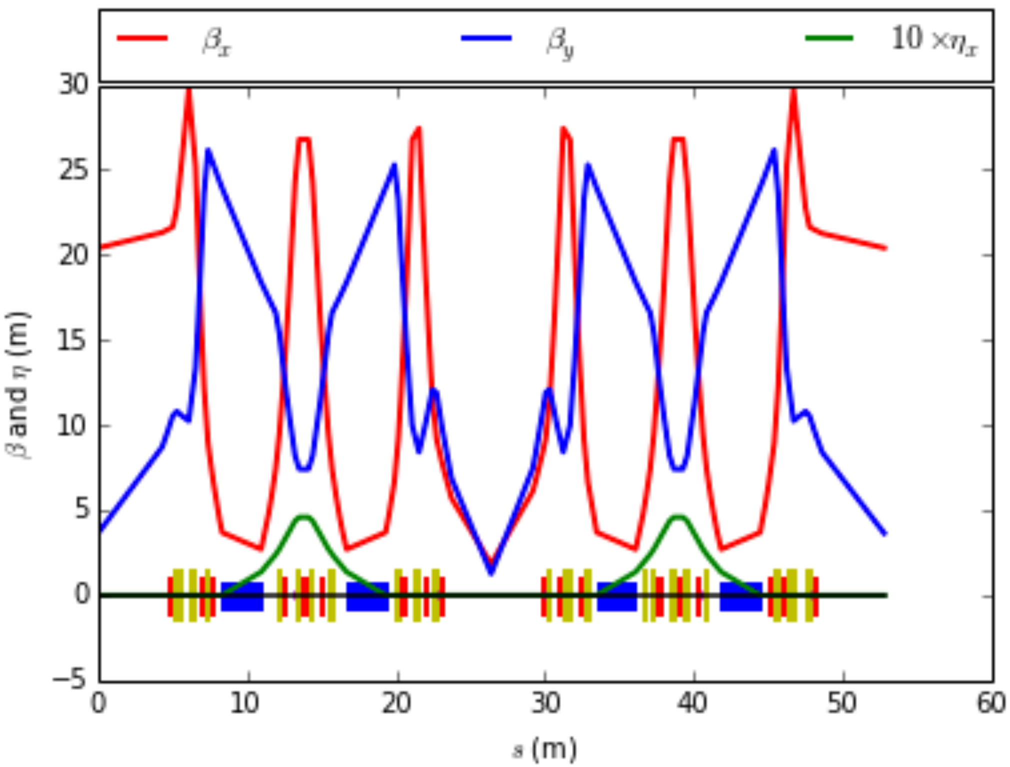
MOGA optimization by varying geometrical sextupoles in NSLS-II

1. Choose the number of initial populations and the number of generations;
2. Start from random seeds for sextupole configuration;
3. For each configuration, calculate NDTs up to 2nd order using the formulae derived by C-X. Wang (**> 30 terms**)
4. Implement standard MOGA iteration
5. **Using DA tracking code to pick the best solution(s) from the last generation**
6. If no satisfied DA is found, repeat step 3-4, or some modification on linear optics might be necessary

A pure Python script of implementing parallel optimization have been developed at BNL.

NSLS-II ring

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



Requirements for DA:

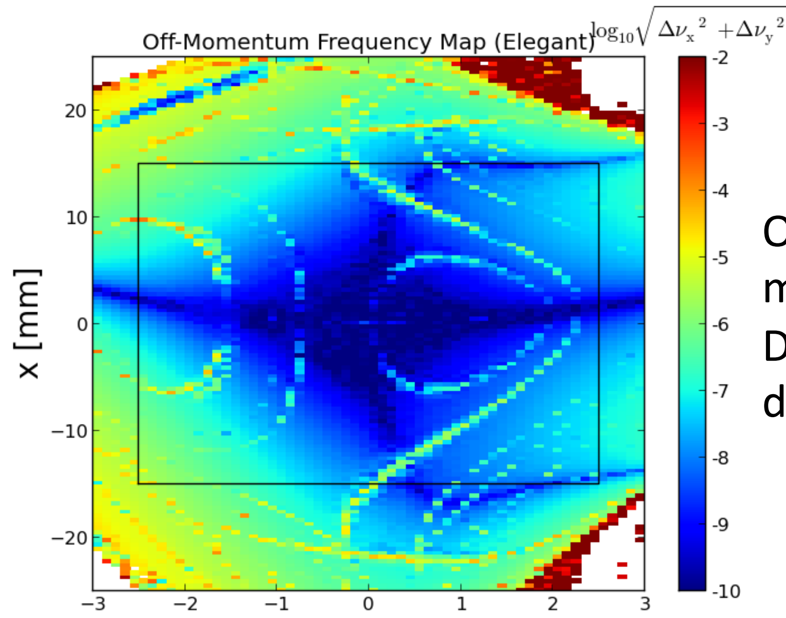
DA >= 15mm at high-beta straight for efficient injection

Energy acceptance >2.5% for sufficient beam lifetime

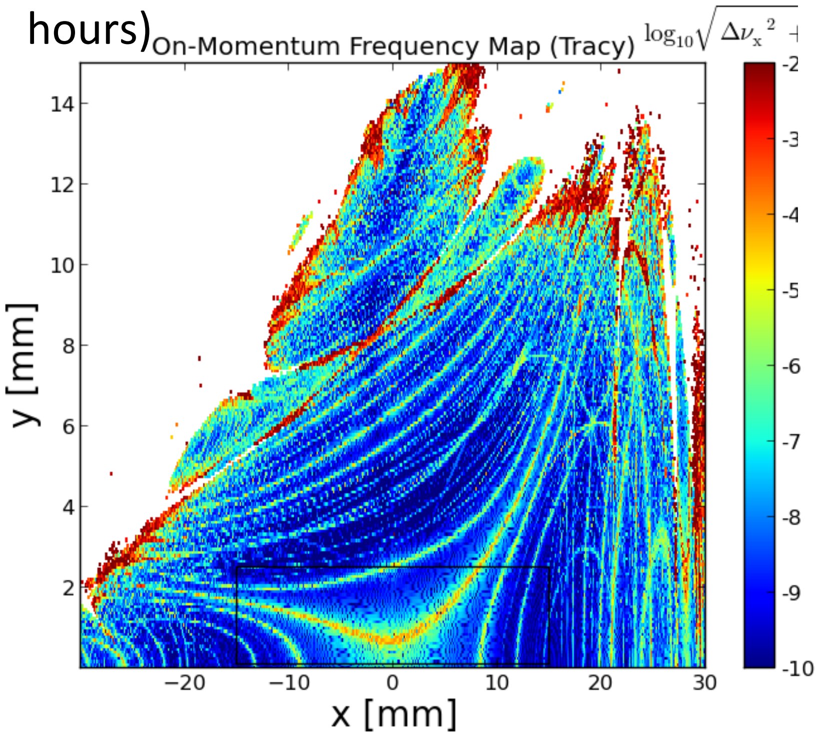
Tolerate numerous insertion devices and engineering errors

Application on NSLS-II bare lattice

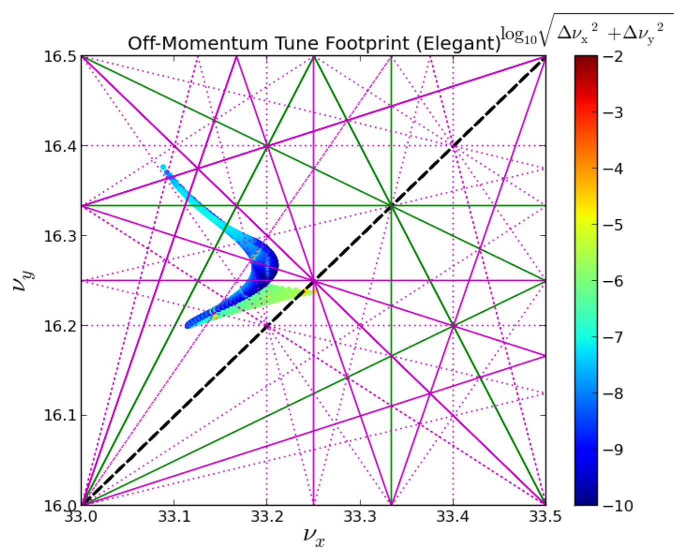
Choosing tune as 33.20/16.25
Using one super-cell for NDT optimization
4000 populations, 100 generations with parallel calculation (several hours)



Off-momentum DA in x-delta plane

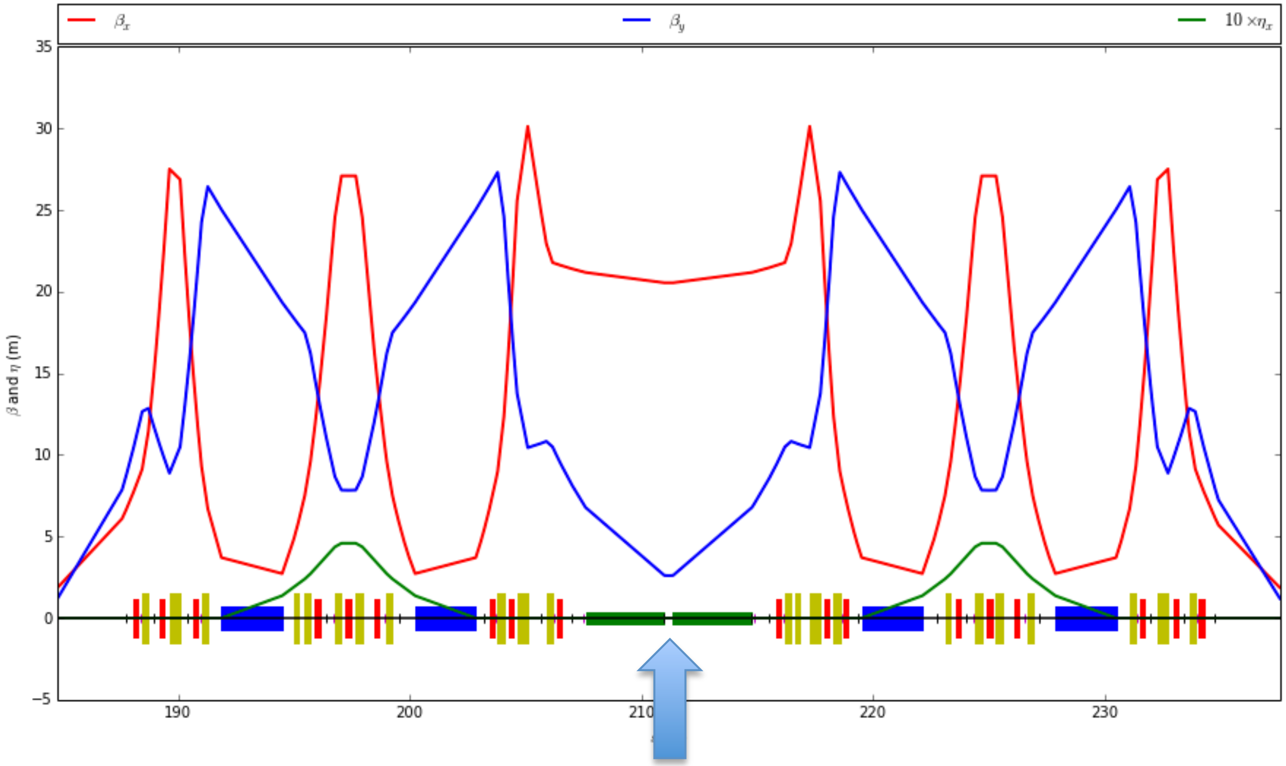


On-momentum DA in x-y plane



Off-momentum tune footprint in tune space

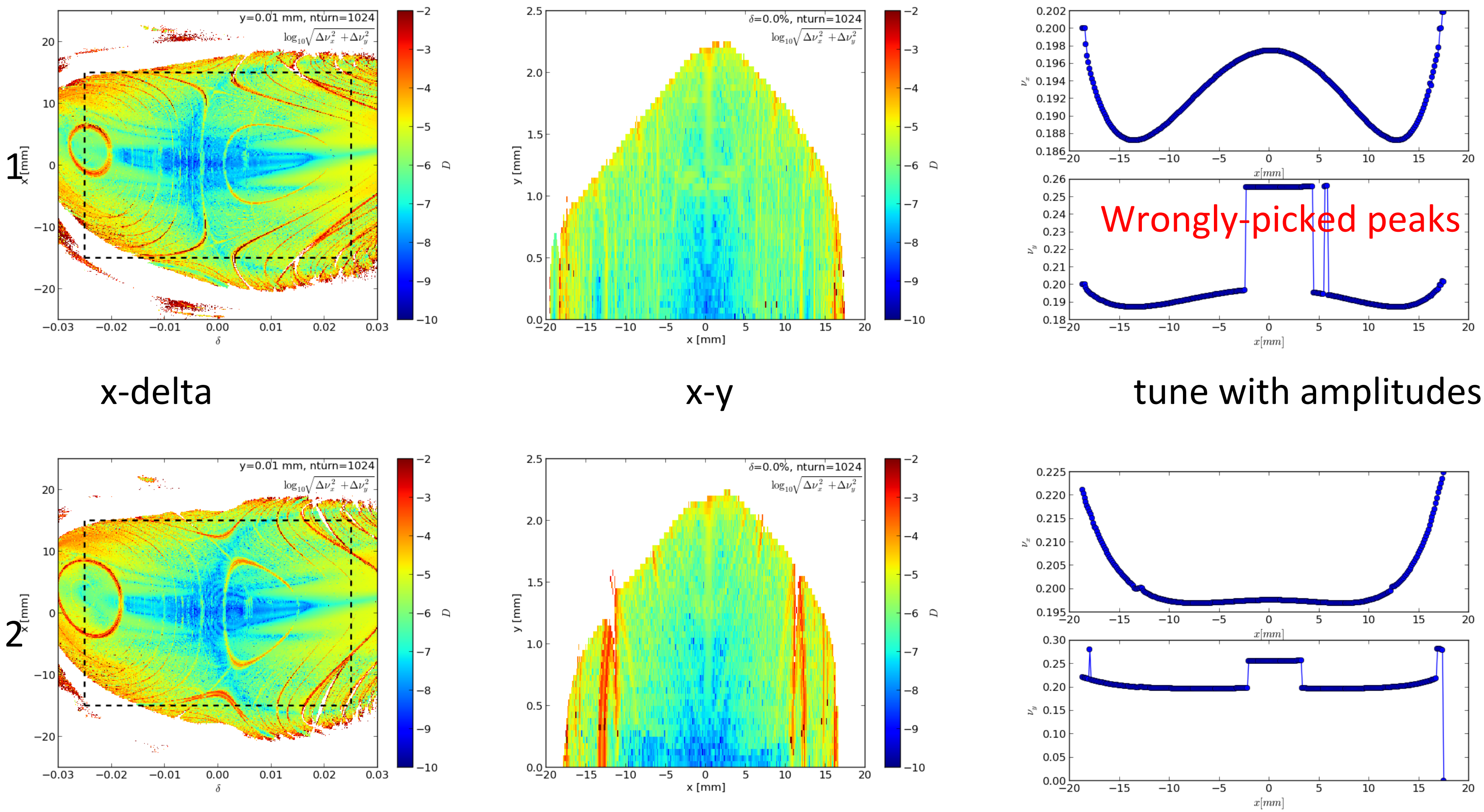
Application on ID integration (damping wigglers as example)



2x3.4 m Damping Wiggler in 1/3 ring

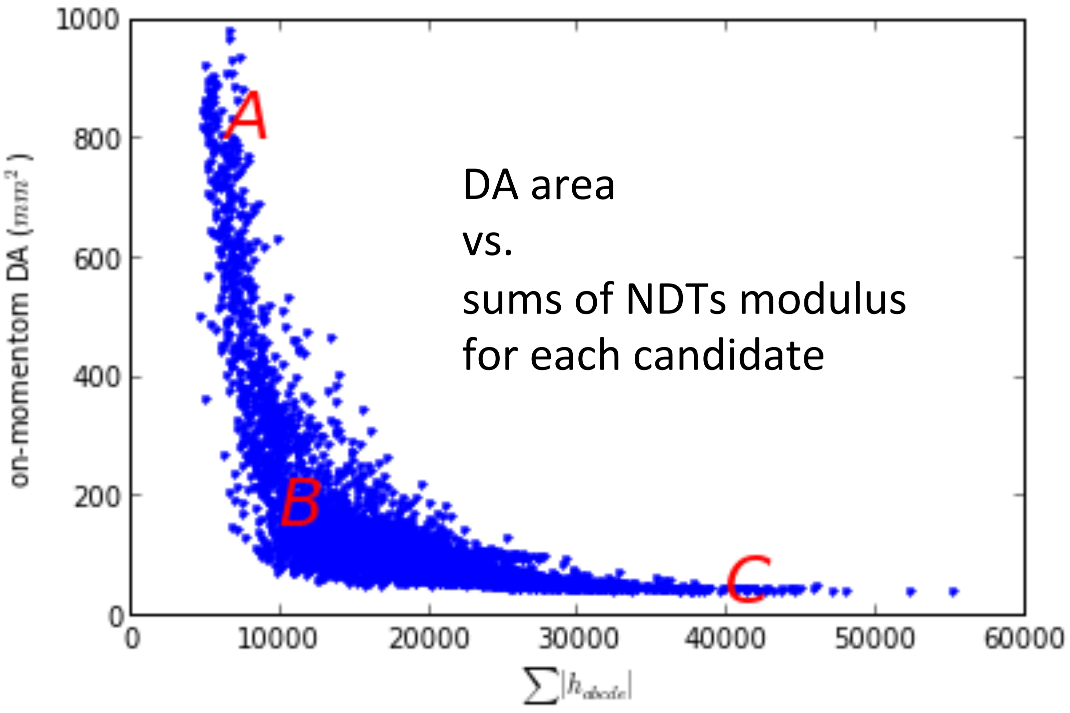
- Match linear optics to accommodate various IDs
- Adjust tune slightly to avoid dangerous resonance line
- Re-run the parallel MOGA optimization

Multiple candidate solutions with one run (engineering tolerance included)



Correlation between DAs and NDTs

for bare lattice



Last generation of
4000 sext. configurations

More analyses are still needed to better understand the correlation

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

Performance comparison between the brute-force method and the new one

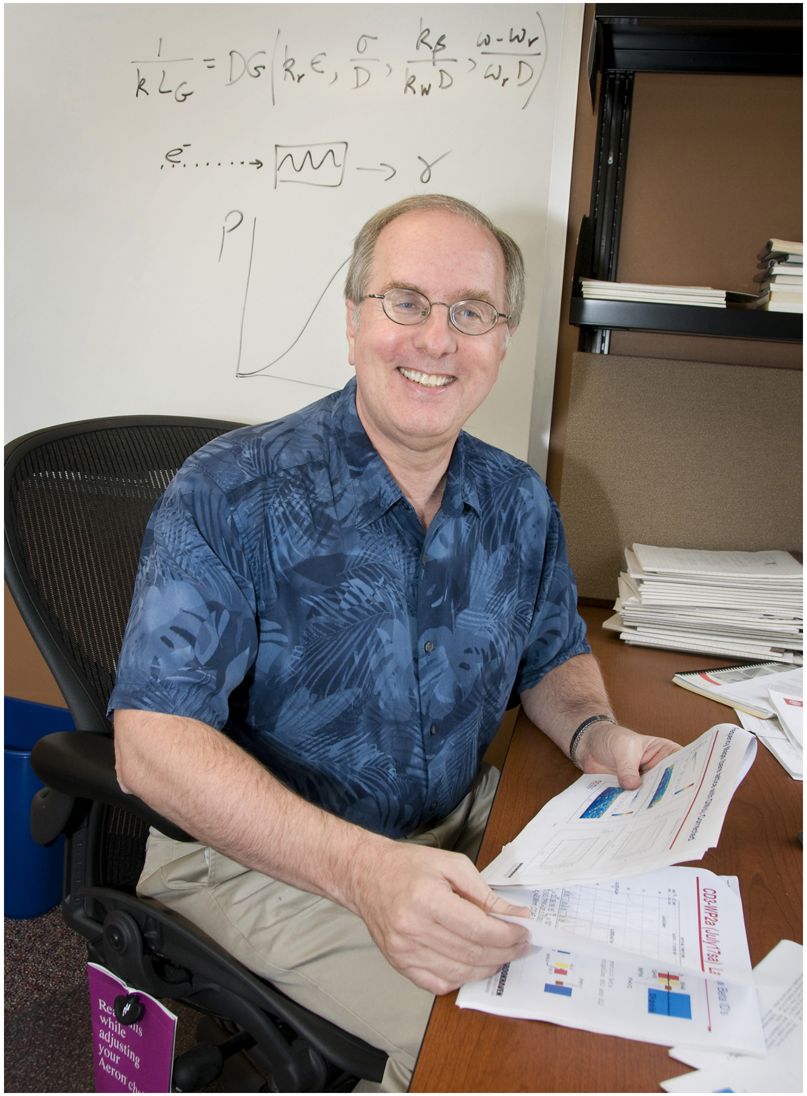
- Brute-force method (L. Yang, and Y. Li, PRST-AB, 2011)

> momentum and off-momentum particles, we use a population of 6000, and run for 300 generations. With 96 xeon 2.33 GHz CPUs in a Sun Grid Engine cluster , it takes less than a week to get a final population shown in Fig. 1.

- New method: It takes less than **12 hours** to finish one run for NSLS-II.

Summary

- Applying MOGA to optimize the nonlinear driving terms is much efficient than the brute-force method of optimizing DA directly.
- Having small low order NDTs is an necessary, but not sufficient condition for have a decent DA.
- Using MOGA, for the first time, we show that in tune space, the area around (33.20/16.25) is a good region having a good DA for the NSLS-II ring (official tune: 33.22/16.26).



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Smooth Accumulation up to 50mA for the first time on July 11, 2014