Ultrafast Beams and Applications 19

Nonlinear dynamics optimization with multi-objective PSO algorithm

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Outline

- Introduction to MO optimization algorithms
    - MOGA
    - MOPSO
- Overview of CANDLE project
- Implementation for CANDLE storage ring
    - Three objective scenario
    - Two objective scenario
- Results
- Summary and outlook

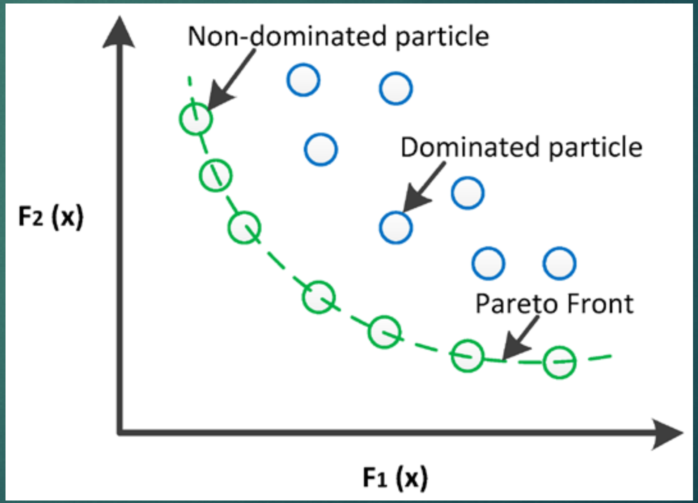
Introduction to MO optimization algorithms

A wide variety of problems in engineering, industry, and many other fields, involve the simultaneous optimization of several (usually conflicting) objectives.
These problems are called Multi-objective Optimization Problems (MOPs).

The multi-objective optimization problem is formulated as follows:

$$\left.\begin{array}{llr} \text{Minimize} & f_m(\mathbf{x}), & m = 1,2,\ldots,M; \\ \text{subject to} & g_j(\mathbf{x}) \geq 0, & j = 1,2,..,J; \\ & h_k(\mathbf{x}) = 0, & k = 1,2,..,K; \\ & x_i^{(L)} \leq x_i \leq x_i^{(U)} \quad i = 1,2,..,n. & \end{array}\right\}$$

An optimal set of solutions (surface) in the objective space is called a Pareto front.



Introduction to MO optimization algorithms

Genetic Algorithms emulate genetic evolution of species in nature:

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

MOGA

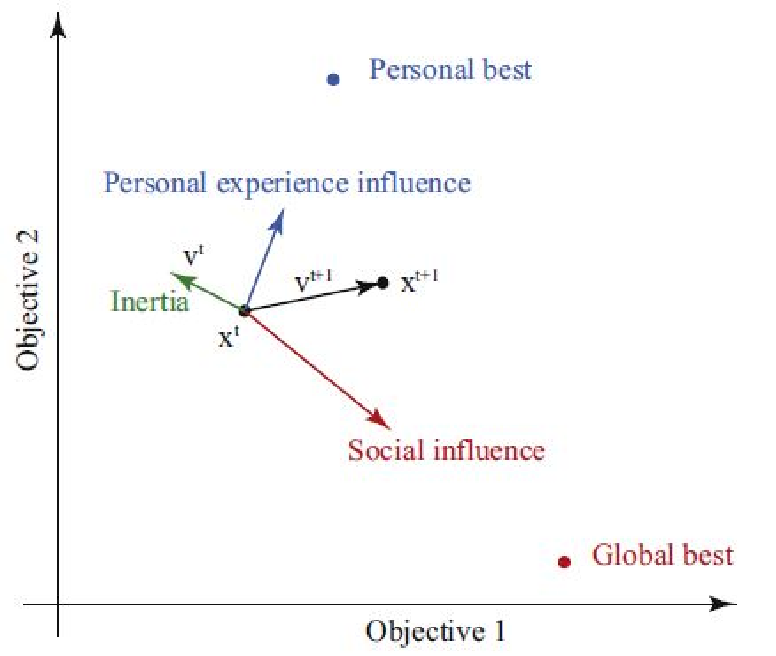
1. Initialize population (first generation)
2. Repeat until the maximum number of iterations is reached or a convergence criterion is met
   - crossover: 2 parents generate 2 children.
   - mutation: change children.
   - calculate children's parameters
   - natural selection: sorting (non-dominated)
3. Select the suitable solution from Pareto front.

Introduction to MO optimization algorithms

PSO emulates the self-organizing behavior of social animals living in groups:

- Each individual's behavior is greatly influenced by both its own personal experience and the social standard.

$$\boldsymbol{v}_i^{t+1} = w\boldsymbol{v}_i^t + c_1 r_1 (\boldsymbol{p}_i^t - \boldsymbol{x}_i^t) + c_2 r_2 (\boldsymbol{g}^t - \boldsymbol{x}_i^t)$$
$$\boldsymbol{x}_i^{t+1} = \boldsymbol{x}_i^t + \boldsymbol{v}_i^{t+1}$$



MOPSO

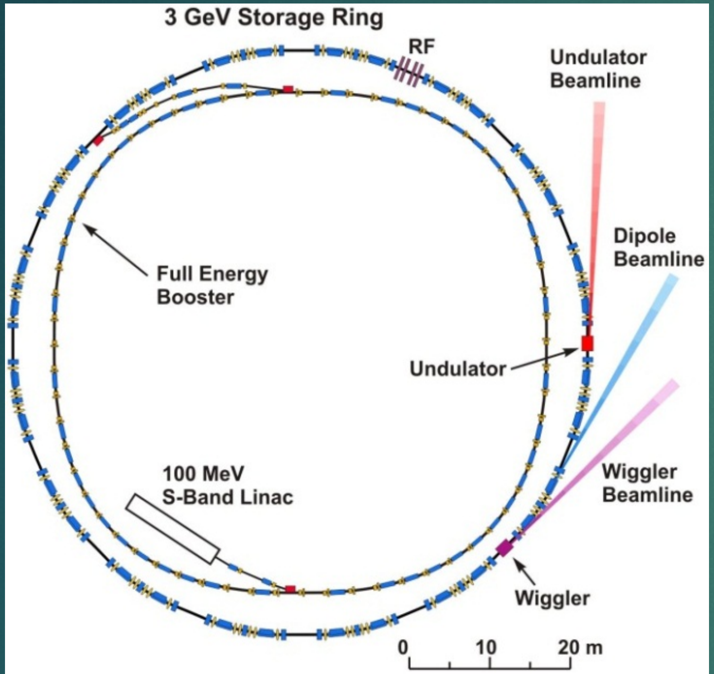
1. Initialize population (first generation positions, velocities, p-bests).
2. Form the g-best archive based on non-dominated solutions.
3. Repeat until the maximum number of iterations is reached or a convergence criterion is met
   - Velocity update
   - Position update
   - Mutate the new positions
   - Update each particle's personal best
   - Update the global best archive

3. Select the suitable solutions from Pareto front.

MOPSO demonstrates much faster convergence while providing comparable solutions with MOGA.

Overview of CANDLE project

CANDLE



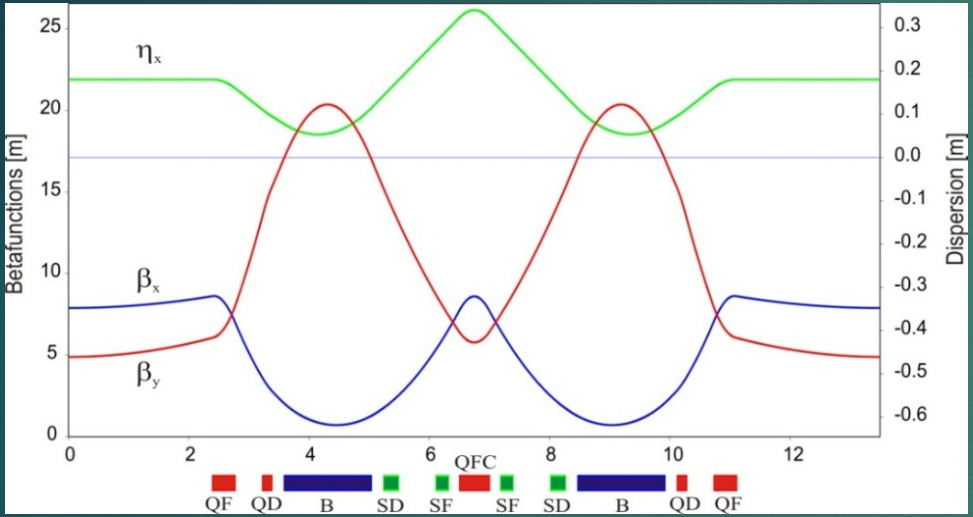
TDR completed in 2002
http://candle.am/design_report/

Parameter	Value
Circumference (m)	216
Number of DBA cells	16
Straight section length (m)	4.8
Beam current (mA)	350
Beam Energy (GeV)	3
Hor. emittance (nm rad)	8.4
RF momentum acceptance (%)	2.4
Betatron tunes (h/v)	13.22/4.26
Natural chromaticities (h/v)	-18.9/-14.9

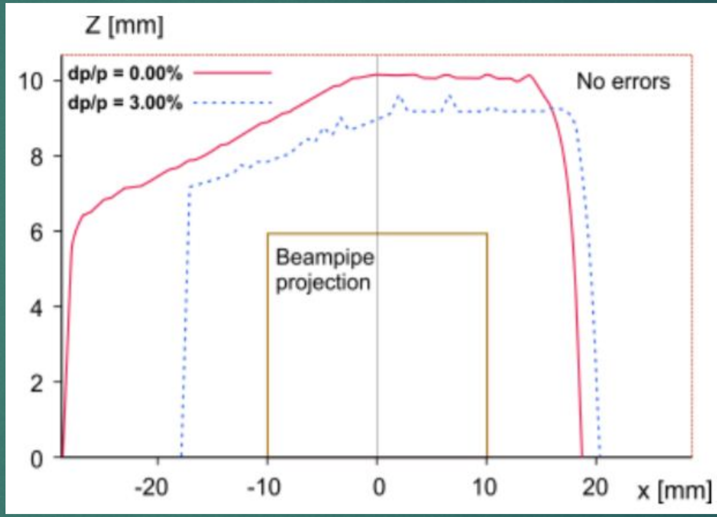
V. Tsakanov et al., Rev. Sci Instr., 73:1411-1413, 2002.

Overview of CANDLE project

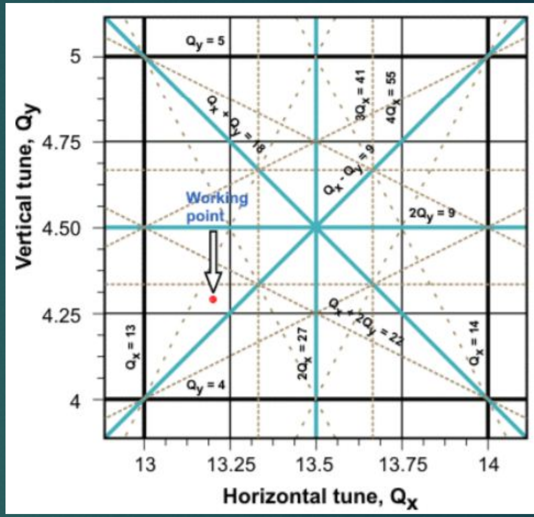
Single cell



Dynamic aperture



Tune diagram



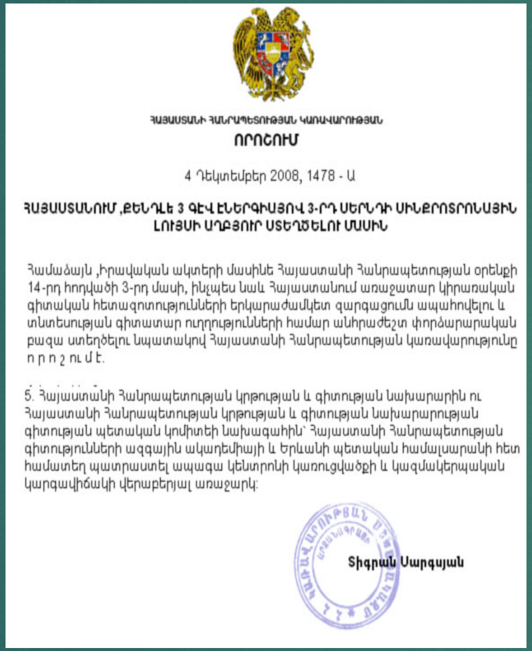
Overview of CANDLE project

International Support

- Letter of Supports
- Memor. of Understanding
- Collaboration Agreements

Overview of CANDLE project

RA Government Resolutions - Dec 2008, May 2010



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ՈՐՈՇՈՒՄ

4 Դեկտեմբեր 2008, 1478 - Ա

ՀԱՅԱՍՏԱՆՈՒՄ ,ՔԵՆԴԼԵ 3 ԳԷՎ ԷՆԵՐԳԻԱՅՈՎ 3-ՐԴ ՍԵՐՆԴԻ ՍԻՆՔՐՈՏՐՈՆԱՅԻՆ ԼՈՒՅՍԻ ԱՂԲՅՈՒՐ ՍՏԵՂԾԵԼՈՒ ՄԱՍԻՆ

Համաձայն ,Իրավական ակտերի մասինե Հայաստանի Հանրապետության օրենքի 14-րդ հոդվածի 3-րդ մասի, ինչպես նաև Հայաստանում առաջատար կիրառական գիտական հետազոտությունների երկարաժամկետ զարգացումն ապահովելու և տնտեսության գիտատար ուղղությունների համար անհրաժեշտ փորձարարական բազա ստեղծելու նպատակով Հայաստանի Հանրապետության կառավարությունը ո ր ո շ ու մ է.

5. Հայաստանի Հանրապետության կրթության և գիտության նախարարին ու Հայաստանի Հանրապետության կրթության և գիտության նախարարության գիտության պետական կոմիտեի նախագահին՝ Հայաստանի Հանրապետության գիտությունների ազգային ակադեմիայի և Երևանի պետական համալսարանի հետ համատեղ պատրաստել ապագա կենտրոնի կառուցվածքի և կազմակերպական կարգավիճակի վերաբերյալ առաջարկ:

Տիգրան Սարգսյան

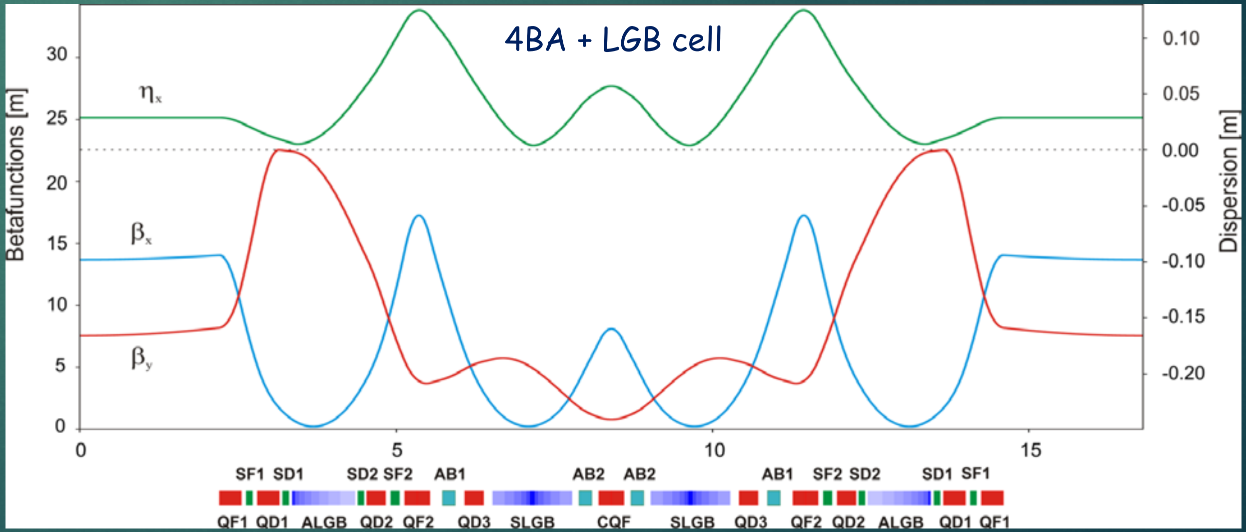
- CANDLE – strategic project for long term development
- The priority program for international cooperation
- Land allocation
- Financial Commitment - 25%

Overview of CANDLE project

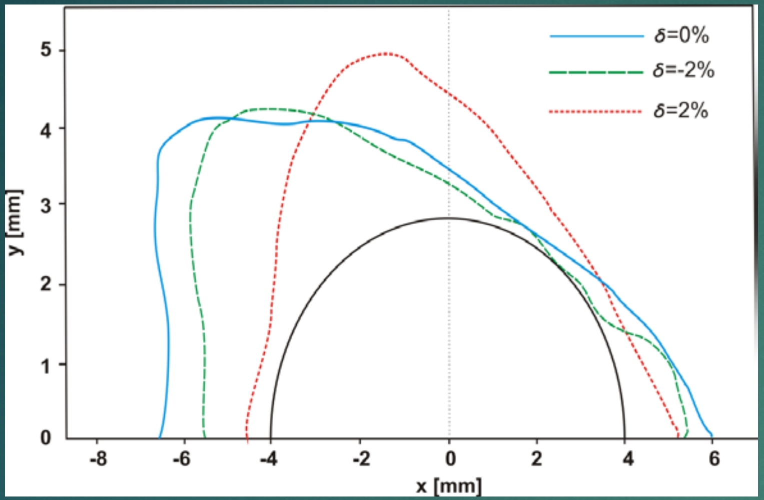
Parameter	Value
Circumference (m)	268.8
Lattice type	4BA
Number of periods	16
Straight section length (m)	4.4
Beam Energy (GeV)	3
Hor. emittance (nm rad)	0.435
RF momentum acceptance (%)	2.6
Betatron tunes (h/v)	29.2/8.36
Natural chromaticities (h/v)	-95.16/ -33.92

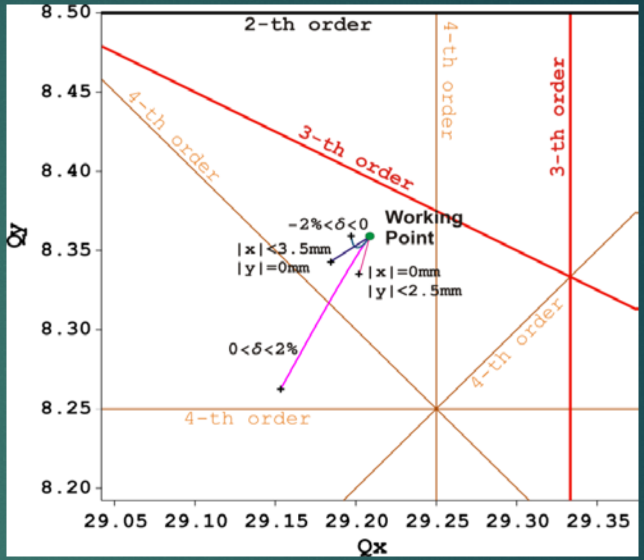
Magnets	Length [m]	Main parameters
ALGB	1	$\alpha = 5^o; B' = -3\frac{T}{m}$
SLGB	1.26	$\alpha = 7.91^o; B' = -7\frac{T}{m}$
Anti-bend (AB1)	0.2	$\alpha = -0.6^o; B' = 5.5\frac{T}{m}; B'' = -300\frac{T}{m^2}$
Anti-bend (AB2)	0.2	$\alpha = -1.06^o; B' = 13.3\frac{T}{m}; B'' = 106\frac{T}{m^2}$
Quadrupoles	0.3-0.4	$\lvert B' \rvert \le 36\frac{T}{m}$
Sextupoles	0.1-0.14	$\lvert B'' \rvert \le 260\frac{T}{m^2}$

Large chromaticities produced by strong quadrupoles of the lattice are corrected by four families of sextupoles (SF1, SF2, SD1 and SD2) and integrated sextupole components of anti-bends (AB1 and AB2).



Overview of CANDLE project



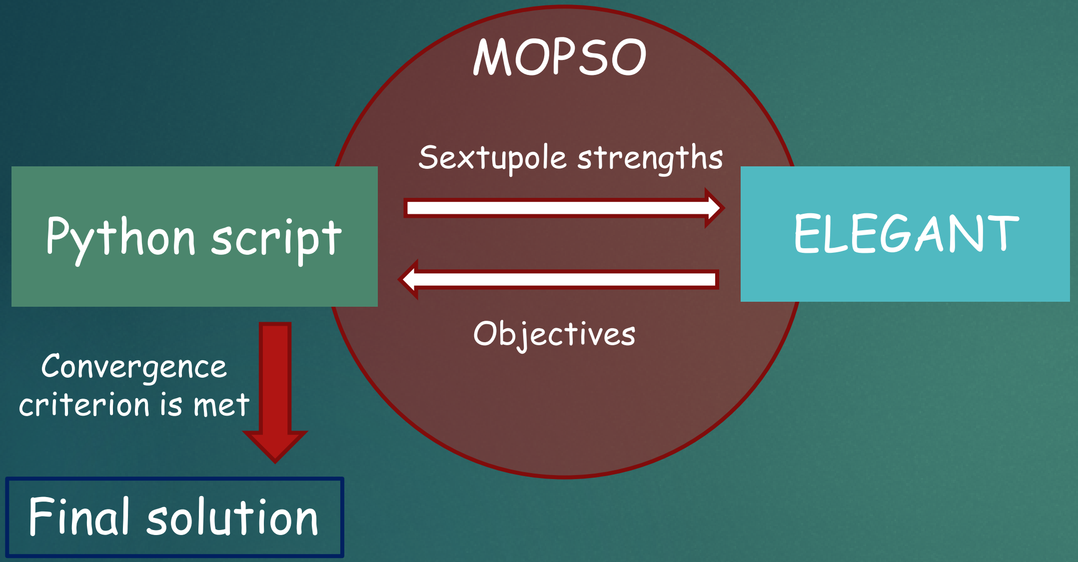


Main drawback is the small value of dynamic aperture. A nonlinear lattice optimization is required to overcome this limitation.

Typical treatments:

- Correction of amplitude-dependent, chromatic tune shifts, and resonance driving terms (RDTs).
- Application of multi-objective optimization (MO) algorithms.

Implementation for CANDLE storage ring



I. Three objectives

Objectives:

- Area of dynamic aperture with restrictions
- Momentum aperture (min value along the lattice)
- Sum of squares of hor. and vert. chromaticities

Knobs:

- SF1, SF2, SD1, SD2, AB1 and AB2

II. Two objectives

Objectives:

- Area of dynamic aperture with restrictions
- Momentum aperture (min value along the lattice)

Knobs:

- SF1, SD1, AB1 and AB2 (SF2, SD2 were used for chromaticity correction using SVD)

Results

I. Three objectives

Objectives:

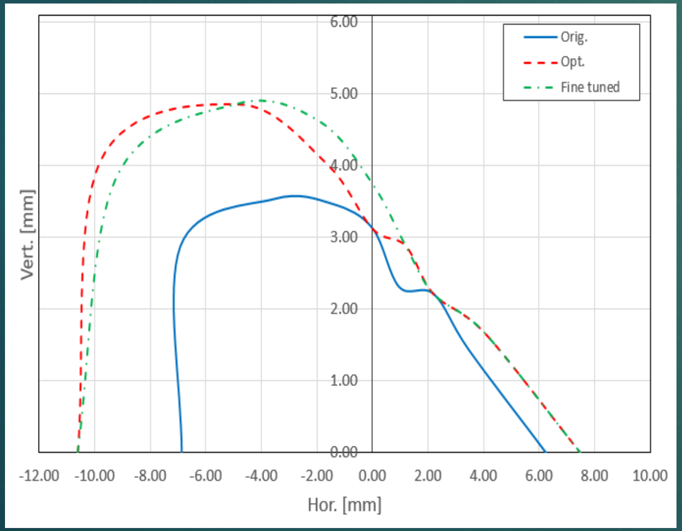
- Area of dynamic aperture with restrictions
- Momentum aperture (min value along the lattice)
- Sum of squares of hor. and vert. chromaticities

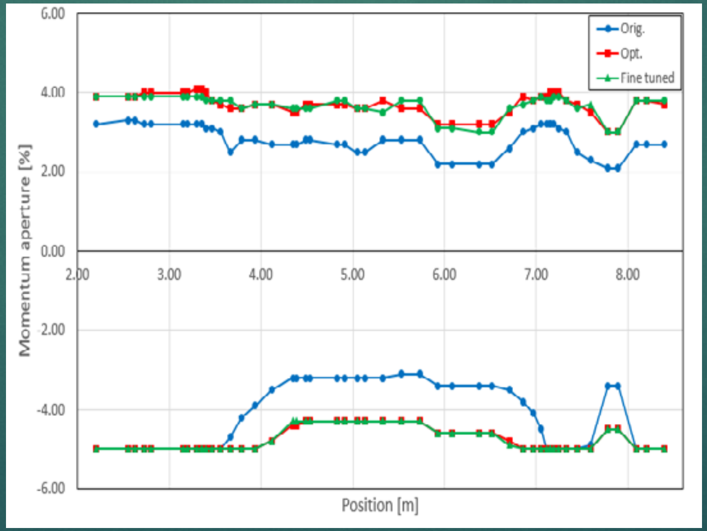
Knobs:

- SF1, SF2, SD1, SD2, AB1 and AB2

The objectives for the best solution are:

- ✓ 44.6 mm^2 for dynamic aperture area
- ✓ 3% for minimum momentum aperture
- ✓ 2.47 for chromaticity term





- The best solution was fine-tuned to ensure zero chromaticities.
- Saturated Pareto front after 60 generations
- Simulations took approximately five days on a single PC.

Results

II. Two objectives

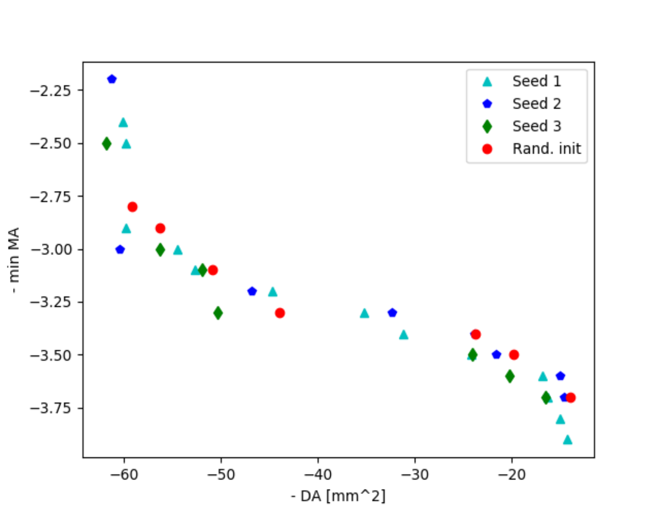
Objectives:

- Area of dynamic aperture with restrictions
- Momentum aperture (min value along the lattice)

Knobs:

- SF1, SD1, AB1 and AB2 (SF2, SD2 were used for chromaticity correction using SVD)

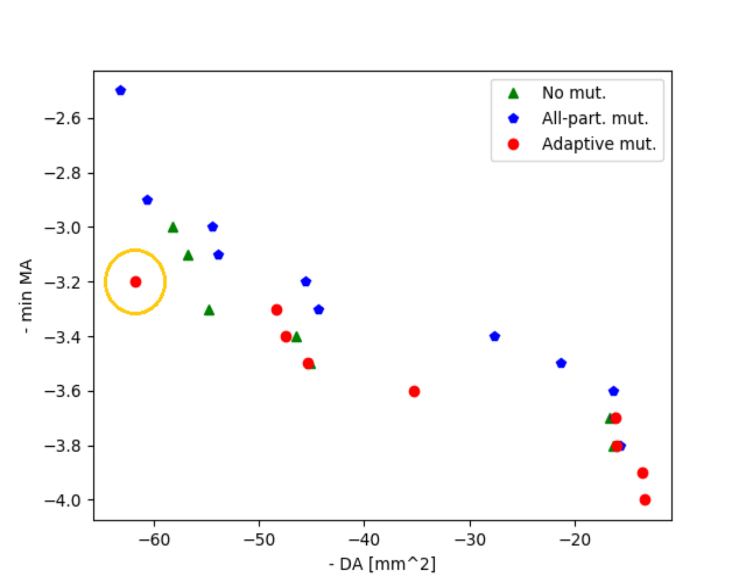
One seed of purely random particle initial positions and three seeds of uniform random distributions around nominal solution within 20% deviation range were considered



Polynomial mutation

$$x_{mut} = x + (x^u - x^l)\delta\ , \begin{cases} \delta = (2r)^{\frac{1}{\eta+1}} - 1 & if\ r < 0.5 \\ \delta = 1 - (2(1-r))^{\frac{1}{\eta+1}} & if\ r \geq 0.5 \end{cases}$$

$$\eta - mut.dist.index, \quad r \in (0,1)$$



Adaptive mutation

The amount of particles affected by mutation is quadratically decreasing with the increase of generation index.

Results

II. Two objectives

Objectives:

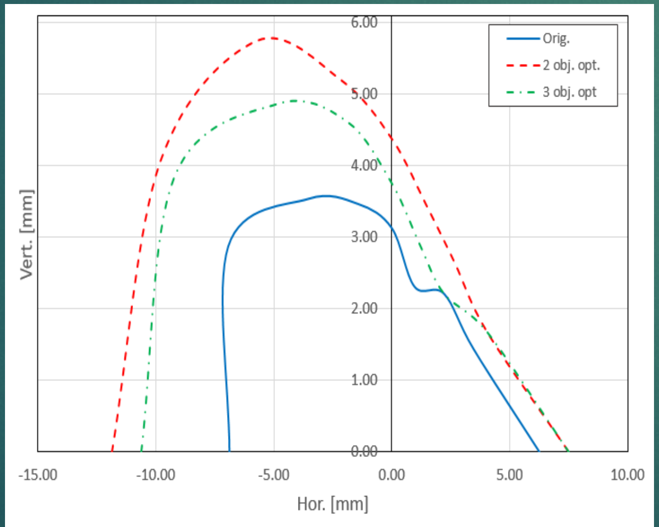
- Area of dynamic aperture with restrictions
- Momentum aperture (min value along the lattice)

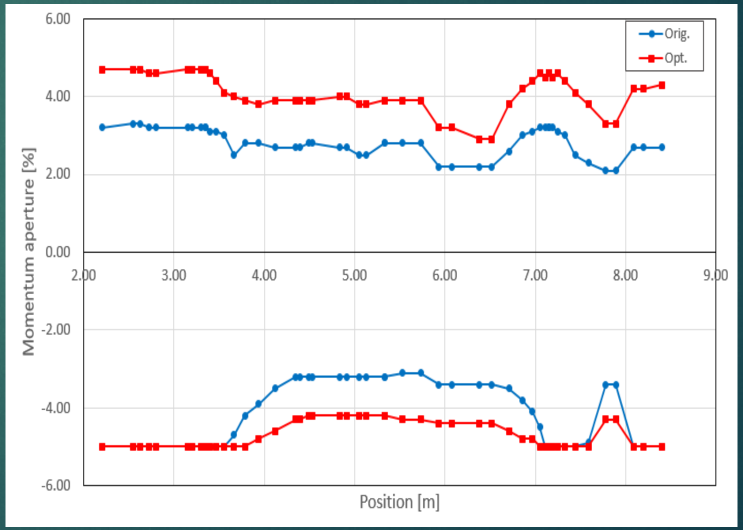
Knobs:

- SF1, SD1, AB1 and AB2 (SF2, SD2 were used for chromaticity correction using SVD)

Obtained best solution:

- ✓ Horizontal DA is between -12 mm and 7 mm
- ✓ Vertical DA reaches up to 5.75 mm
- ✓ LMA increased from 2.1% to 2.8% exceeding 2.6% MA defined by long. dynamics





Summary and outlook

- The two-objective scenario is more preferable than the three-objective one, since it converges faster and provides better solution.
- For the optimized lattice the area of dynamic aperture is about twice larger as compared with original one, while the local momentum aperture exceeds the one coming from longitudinal dynamics.
- A detailed study of various implementation scenarios, especially concerning the mutation operation is foreseen.

V.V. Sahakyan and A.A. Sargsyan, Journal of Instrumentation, Volume 14, April 2019

THANK YOU FOR ATTENTION