Experience with Online Optimizers for APS Linac Front End Optimization

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- Optimize L3:CM1 charge with RG1 gun (new gun)
  - using different optimizers
  - no good configuration, start from scratch
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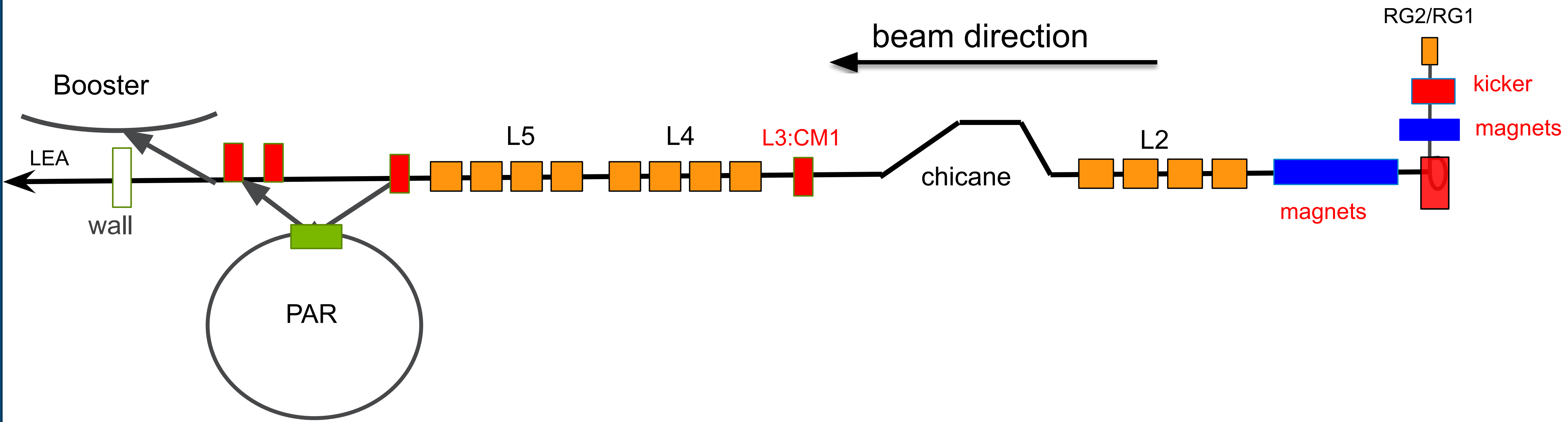
Introduction: APS Linac



- APS linac charge transportation is maximized by:
  – In operation: a simplex optimizer to maximize charge (L3:CM1 charge) with gun front end quadrupoles and steering magnets (16 magnets) (kicker voltage is fixed)
  – A steering controllaw to adjust the linac trajectory (15 magnets in each plane)
  – RG2: 4 magnets used in steering controllaw, 16 magnets → 12 magnets
  – RG1: new gun, starting from scratch, different combinations of magnets

Optimizers

- Simpex (C): APS operation
- MG-GPO: Multi-objective multi-generation Gaussian process optimizer for design optimization (X. Huang, M. Song, Z. Zhang) (matlab)
- MOPSO: Multi-objective multi-generation particle swarm optimization (implemented by X. Huang) (matlab)
- RCDS (X. Huang): Robust conjugate direction search
    - converted in c (sddsoptimize, Shang)

Figure courtesy of Zhe Zhang

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L3:CM1 Charge Optimization with RG2 Gun

- Operation gun, beam stable
- Steering controllaw suspended
- Input variables: 12 RG2 magnets
- Objective: L3:CM1 charge

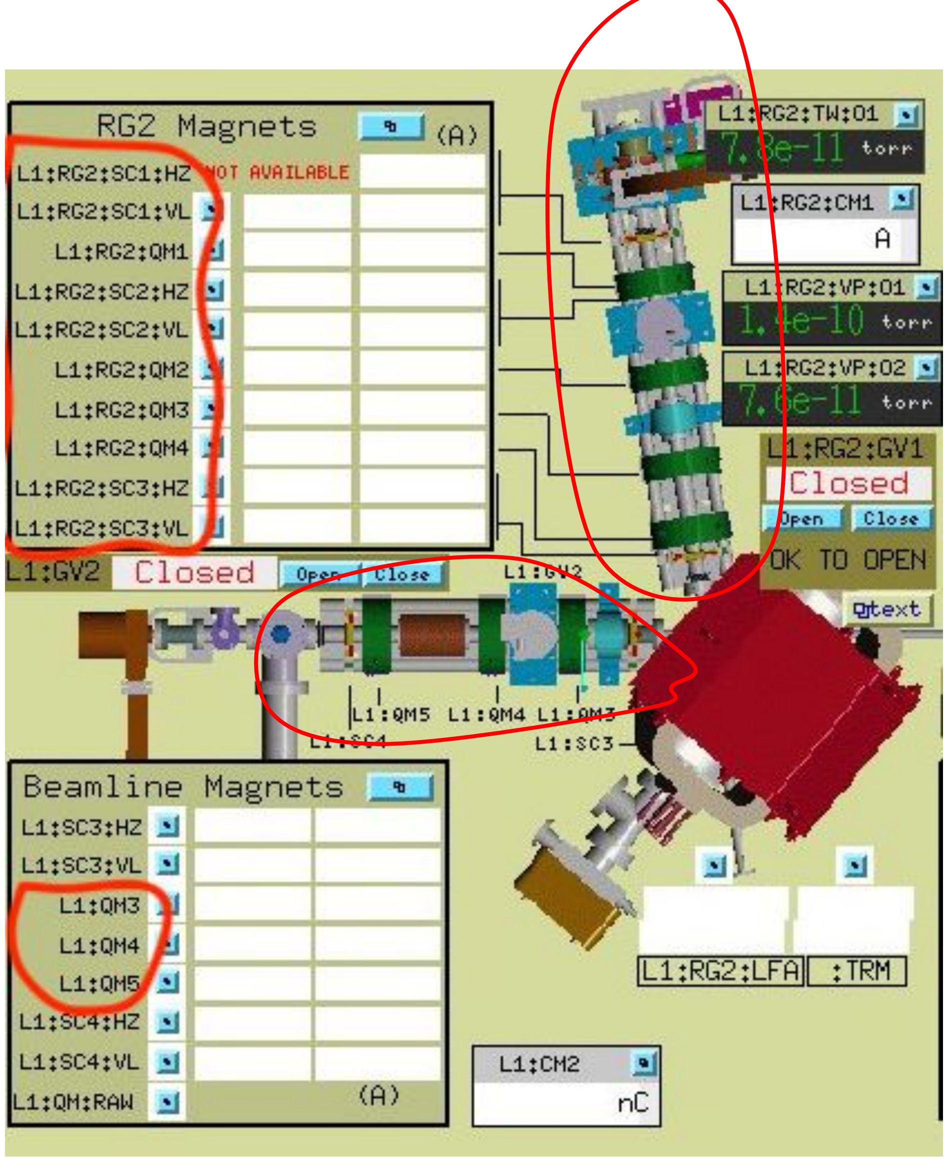


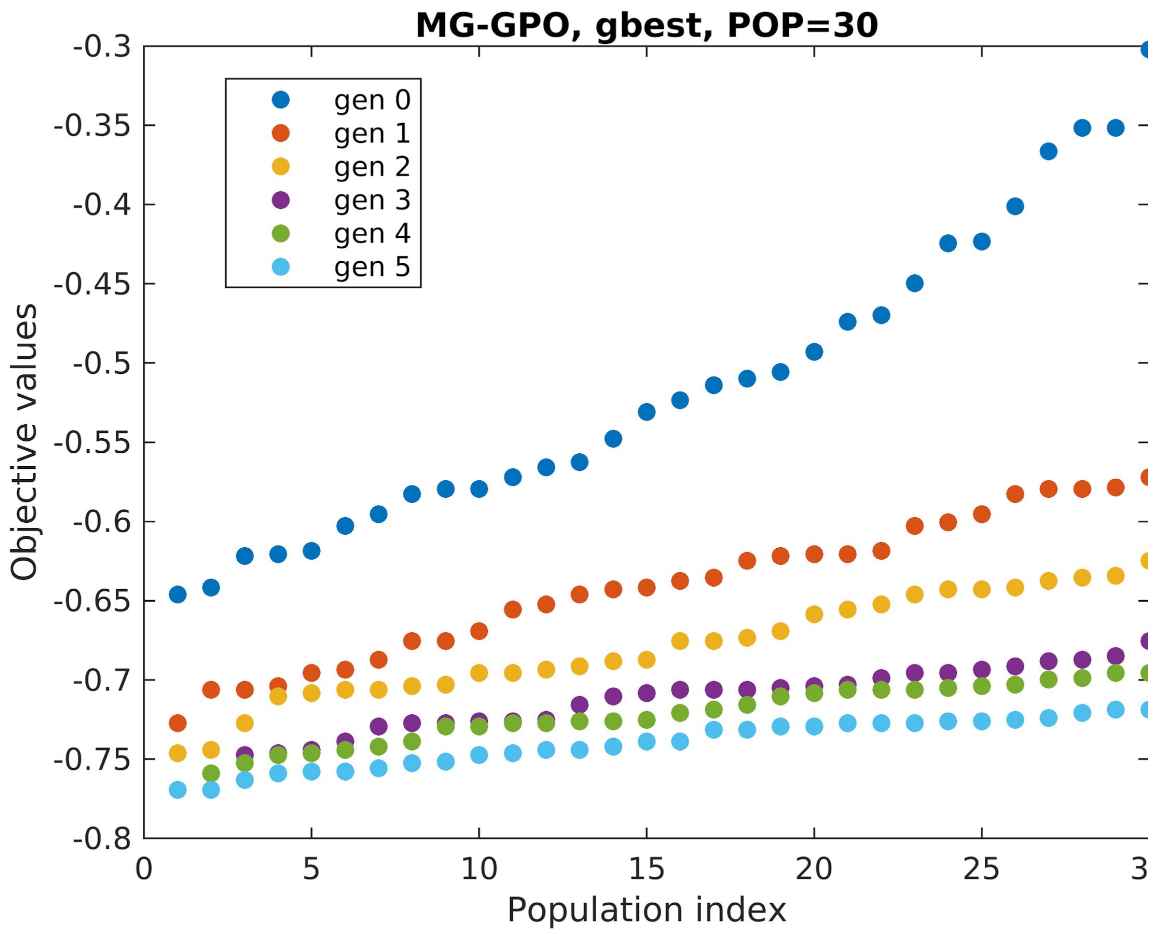
Figure 2. RG2 magnets + L1 quadruples after RG2

L3:CM1 Charge Optimization with RG2 Gun MG-GPO

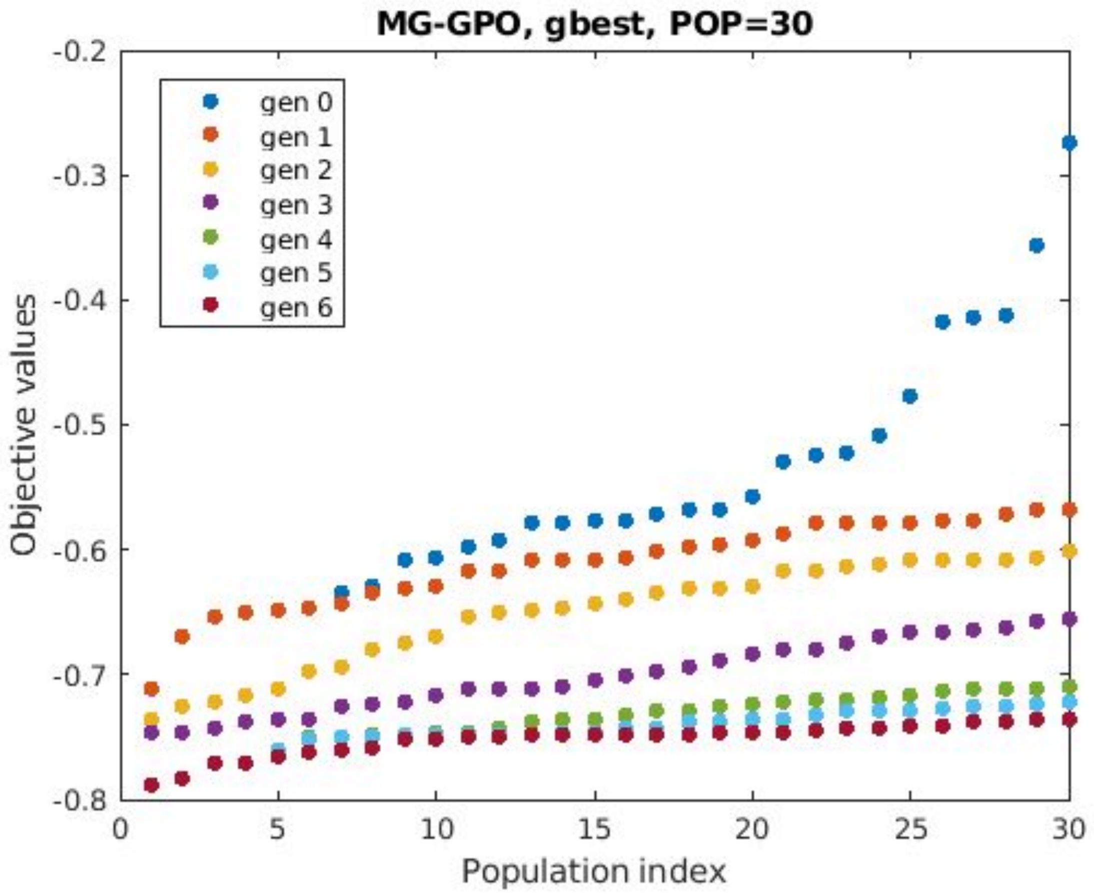
- Start from current operation condition (initial L3:CM1 charge was ~0.63nC)
- To avoid the hysteresis problem, added 0.1 factor to the step-size in the optimizer and changed the corrector range to initial_value +- 0.5A.
- Both non-optimized and optimized hyper-parameters MG-GPO successfully increased L3:CM1 charge from 0.60nC to 0.75nC.
- Non-optimized MG-GPO took about 160 evaluations, optimized MG-GPO took about 140 evaluations to find the best solution. Optimized MG-GPO is faster and more stable.
- Better than our operation condition (optimized from classic optimizer)
- Kicker voltage was 13.8kV.
- GP (gaussian processor) optimizer was not successful with good initial condition. (2019)

L3:CM1 Charge Optimization with RG2 Gun MG-GPO

Start from current operation condition (initial L3:CM1 charge was ~0.63nC)



MG-GPO hyper parameter without optimization



MG-GPO hyper parameter with optimization

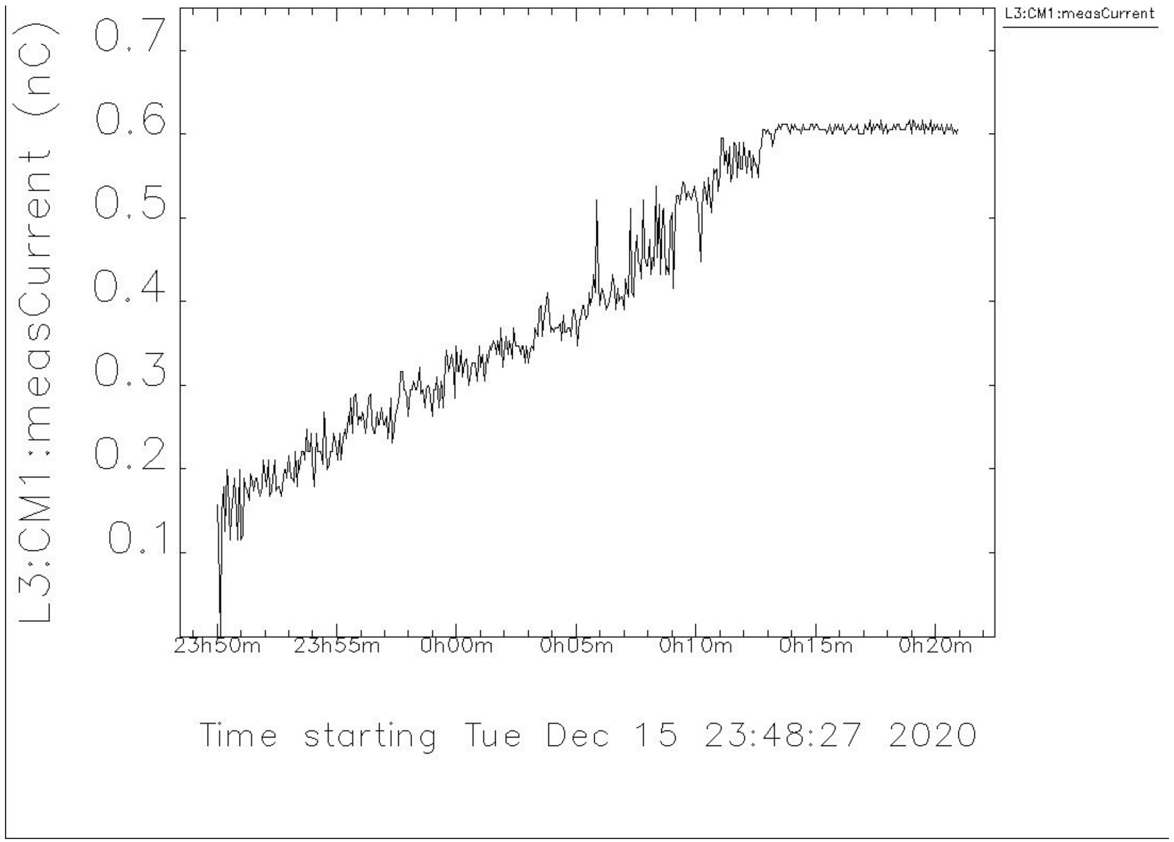
Kicker voltage was 14.0kV

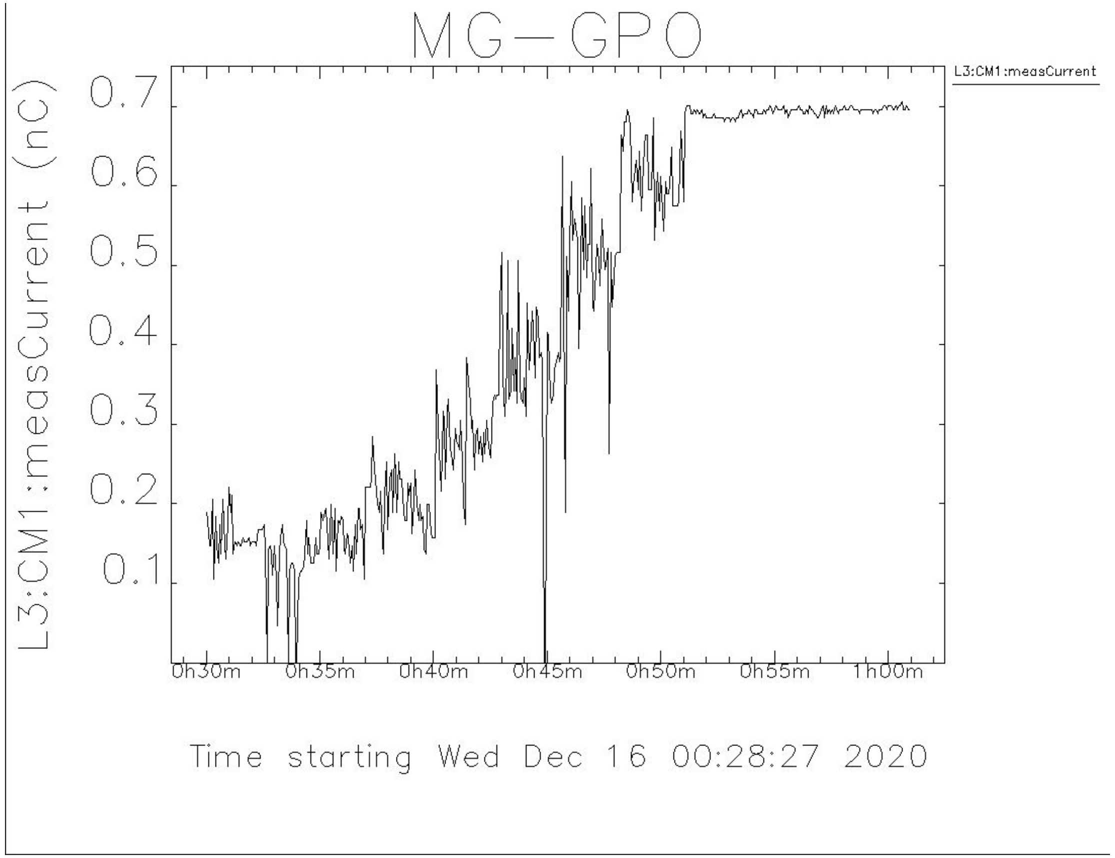
Faster and Better solution

L3:CM1 Charge Optimization with RG2 Gun MG-GPO and MOPSO

Initial State: L3:CM1 ~0.2nC, 12.8kV (kicker), LPL2020-351-1216-002740.gz

MOPSO



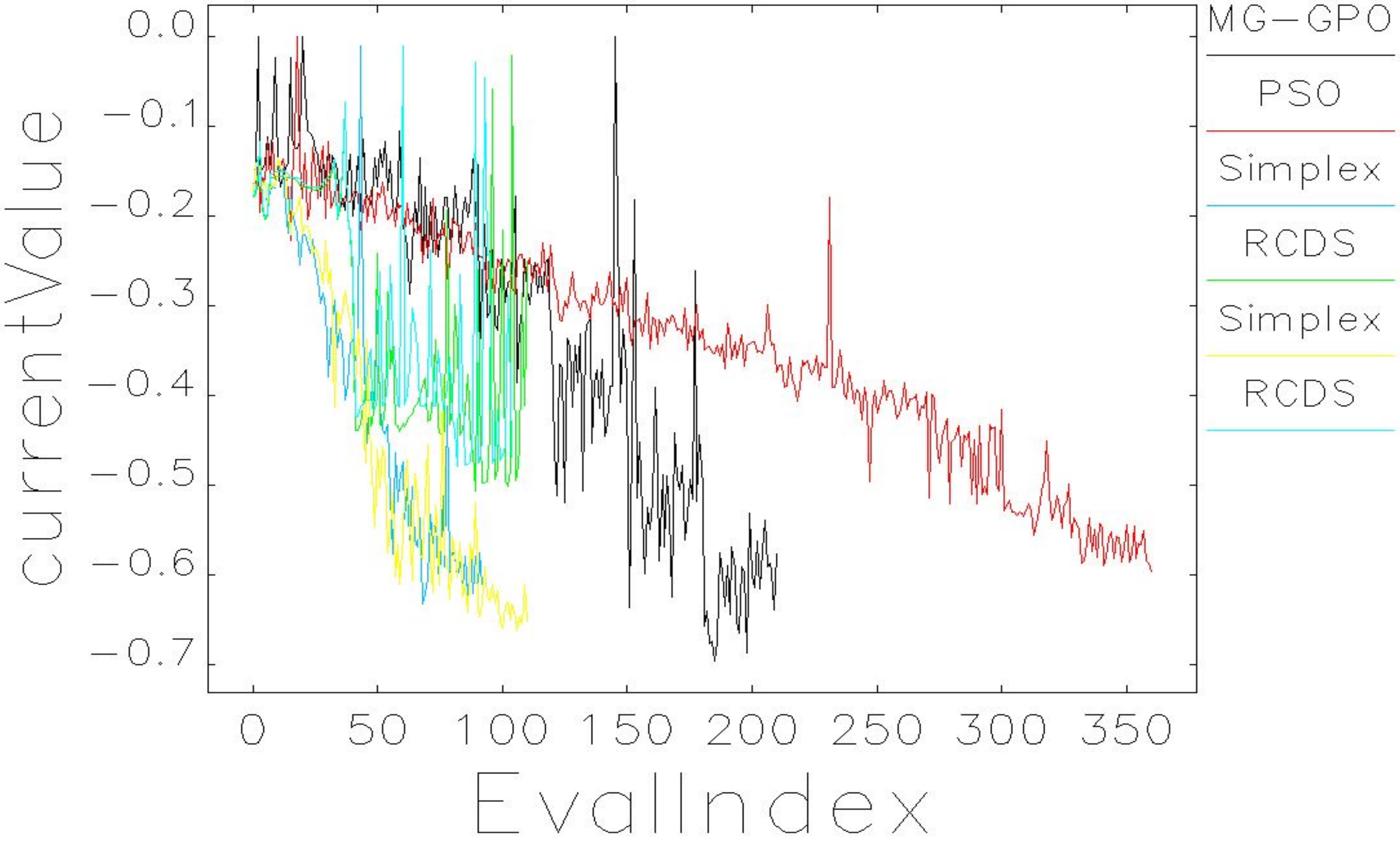


MOPSO obtained 0.6nC L3:CM1 charge (stable), took ~30 minutes

MG-GPO obtained 0.7nC L3:CM1 charge (stable), took ~13 minutes

L3:CM1 Charge Optimization with RG2 Gun

Initial State: L3:CM1~0.2nC, 12.8kV (kicker)

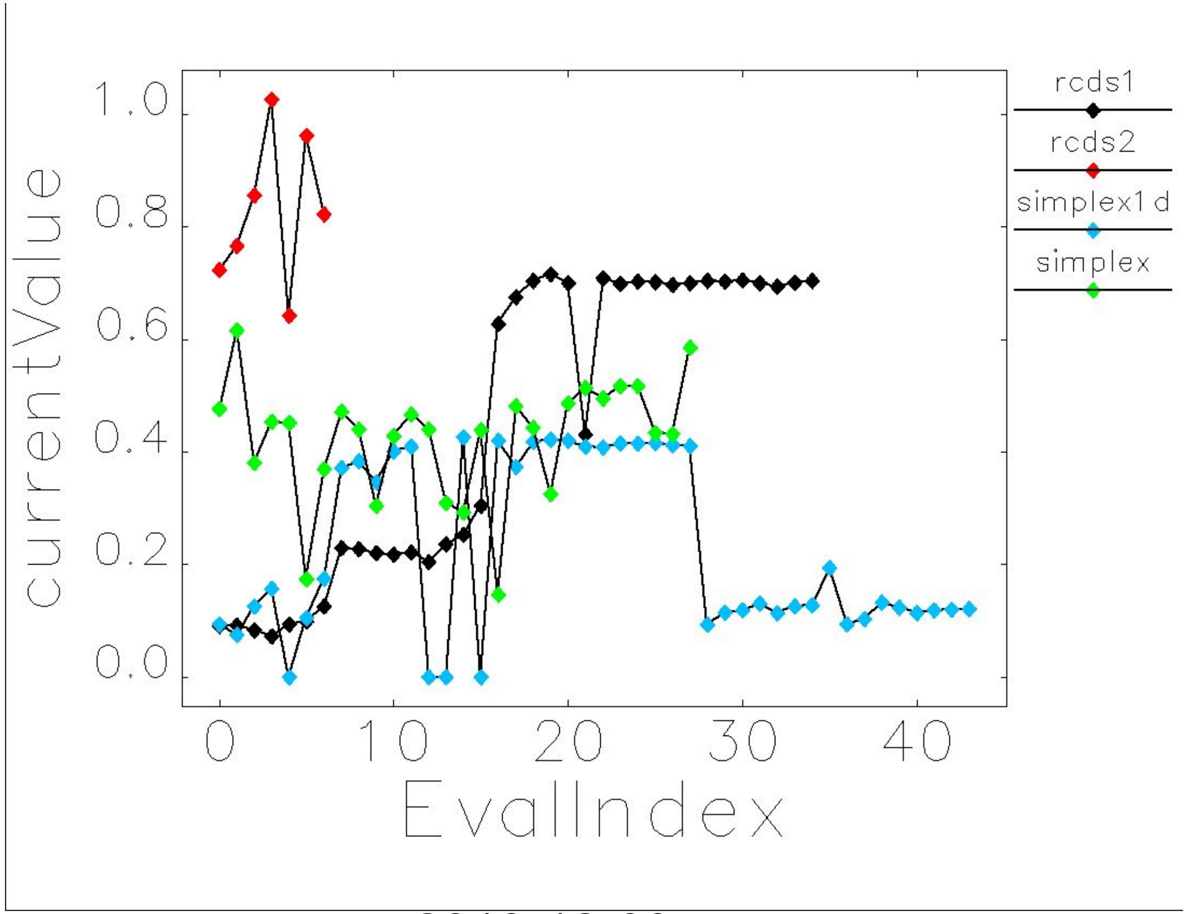


- MG-GPO: better solution
- Simplex: good, the fastest
- RCDS ~0.5nC
- PSO: stable, slow

MG-GPO, PSO 12/16/2020
RCDS, Simplex 1/16/2021

L3:CM1 Charge Optimization with RG2 Gun

- LPL2021-017-0117-123647.gz 0.1nC at 13.5kV kicker, 150mA RG2 gun current (12/9/2019)
  0.05nC at 12.8kV kicker voltage, 120mA RG2 gun current (1/7/2021)
- Run simplex first, only got 0.06nC.



2019-12-09
target >1.0nC

Simplex replies on the initial condition more than other optimizers

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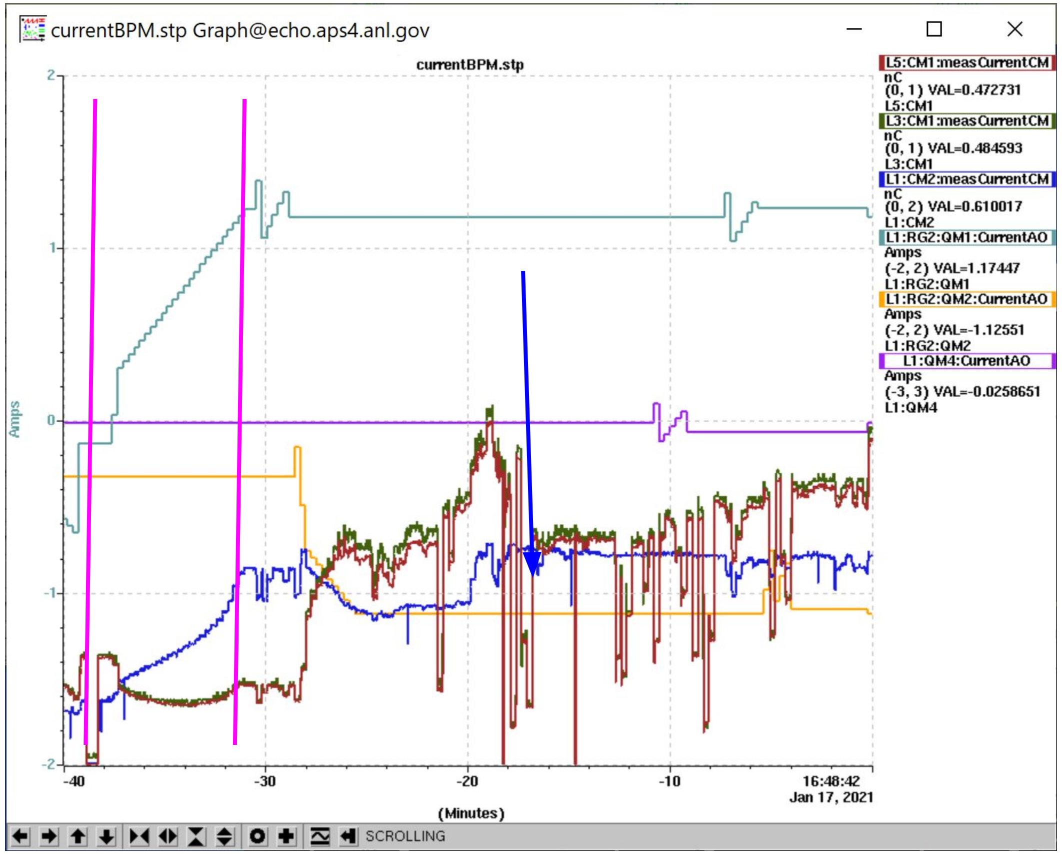
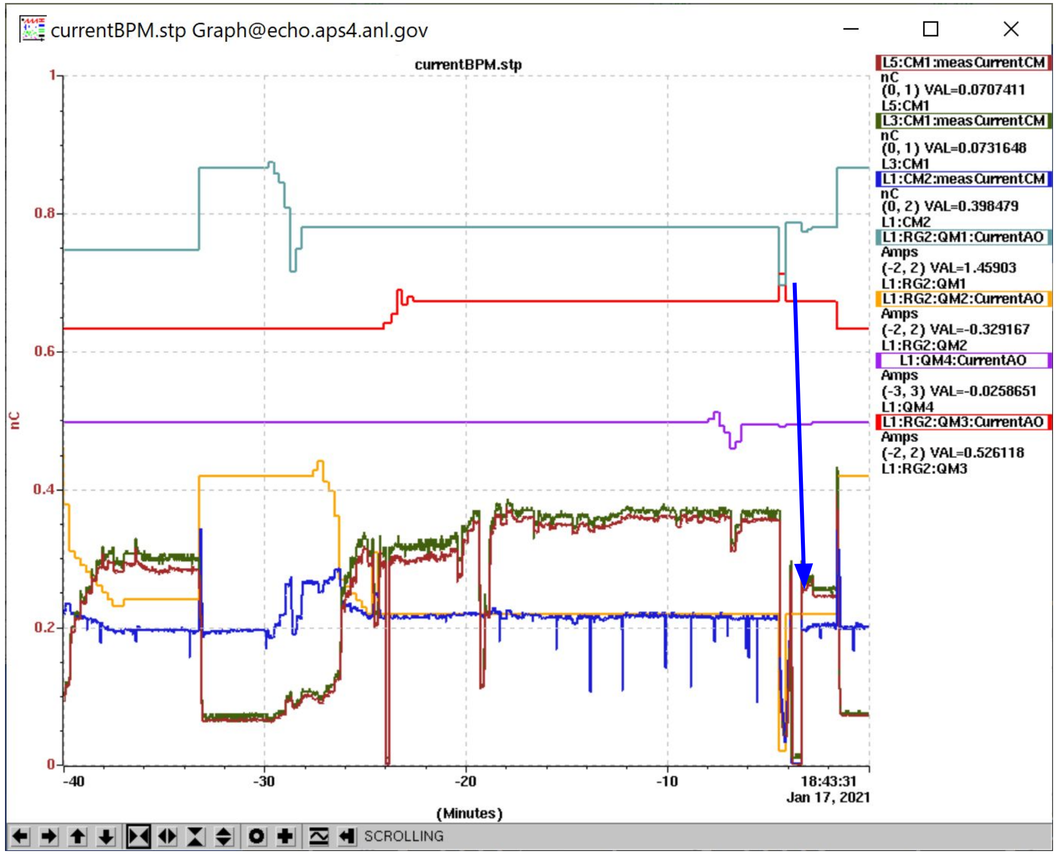
L3:CM1 Charge Optimization with RG2 Gun: RCDS 1/17/2021

- Initial state: 0.06nC at 12.8kV kicker voltage, 120mA RG2 gun current (1/7/2021)
- Initial state config file; LPL2021-017-0117-125213.gz
- Fixed initial step size bug (was hard-coded as 0.01, could not change it before)



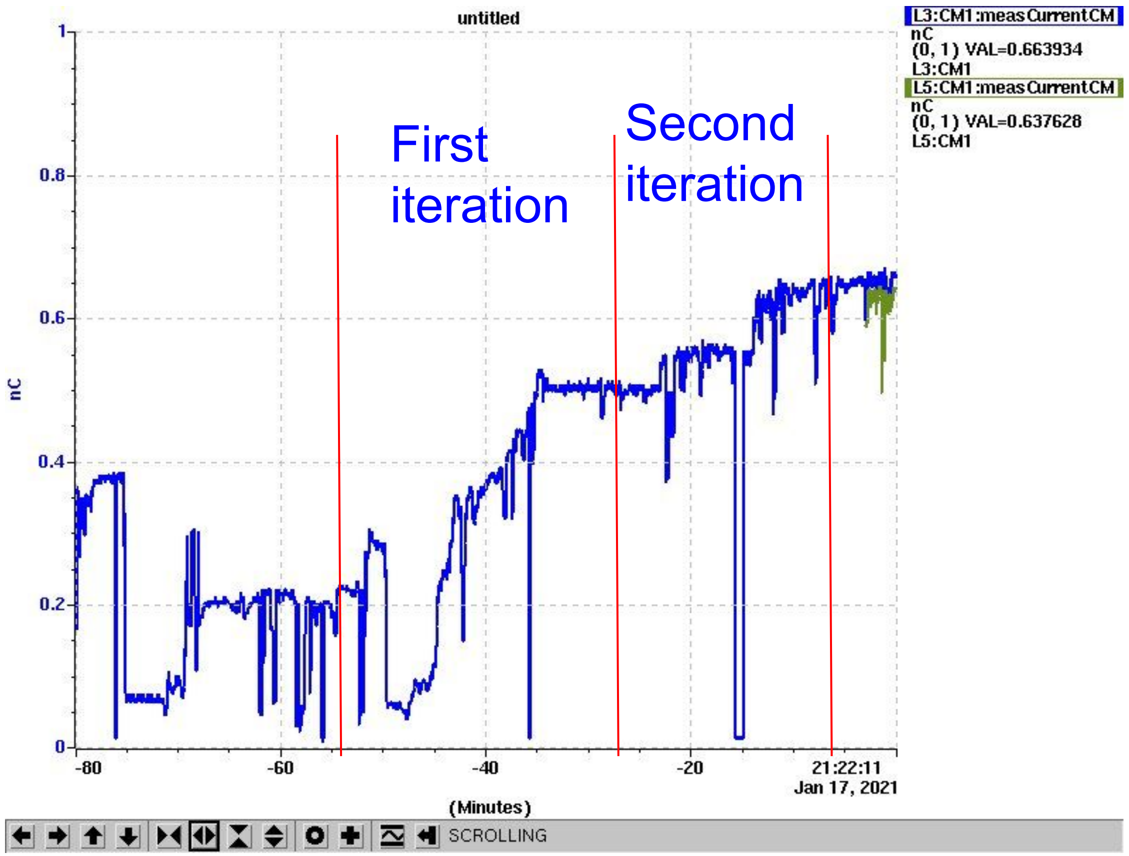
RCDS Noise 0.02, step 0.01
Noise too big, it took a long time scanning RG2:QM1

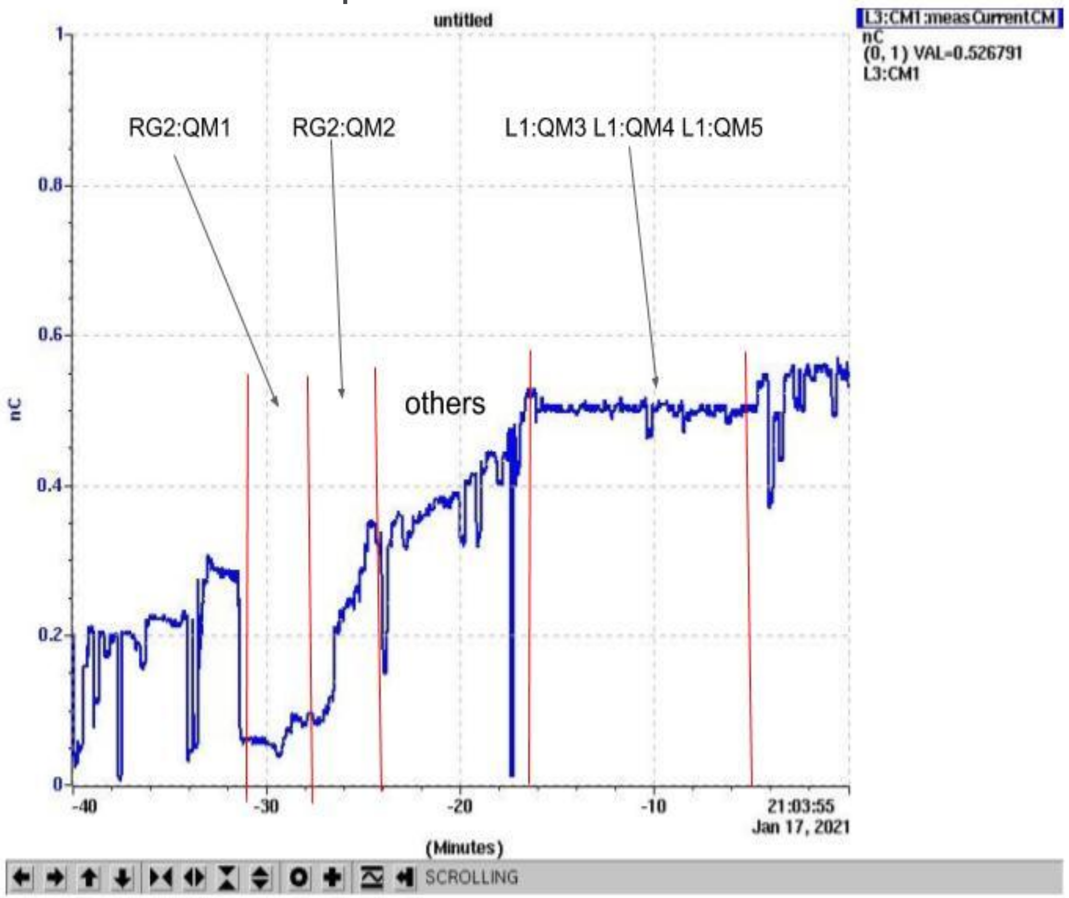


RCDS Noise 0.003, step 0.01

L3:CM1 Charge Optimization with RG2 Gun: RCDS 1/17/2021 (contin.)

- Modified to start with the best solution it obtained for each bracketmin and linescan (RCDS routines)
- Noise 0.003; step 0.02 (smaller noise exist bracketmin loop early, bigger noise help find better solution)
- Further improvement: exist bracketmin (linescan) loop earlier if there is no improvement
  - L1:QM3 L1:QM4 L1:QM5 scan took about 10 minutes with no improvement





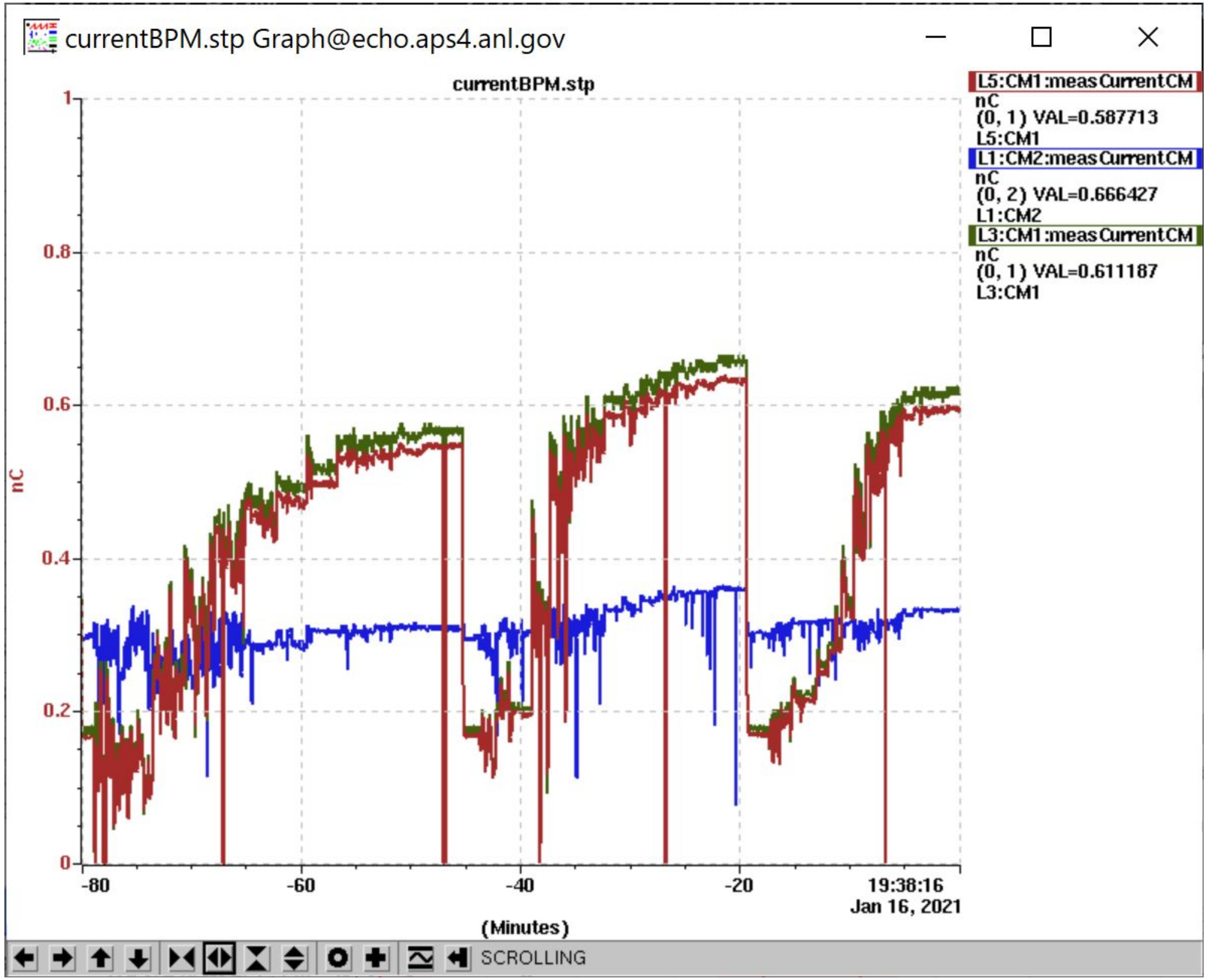
RG2:QM2 is the most effective knob, agree with ML analysis

L3:CM1 Charge Optimization with RG2 Gun: MG-GPO tuning 1/16/2021

- Npop -- smaller → faster; bigger → better solution
- Step size, bigger → search range bigger, may → better solution (hysteresis problem)

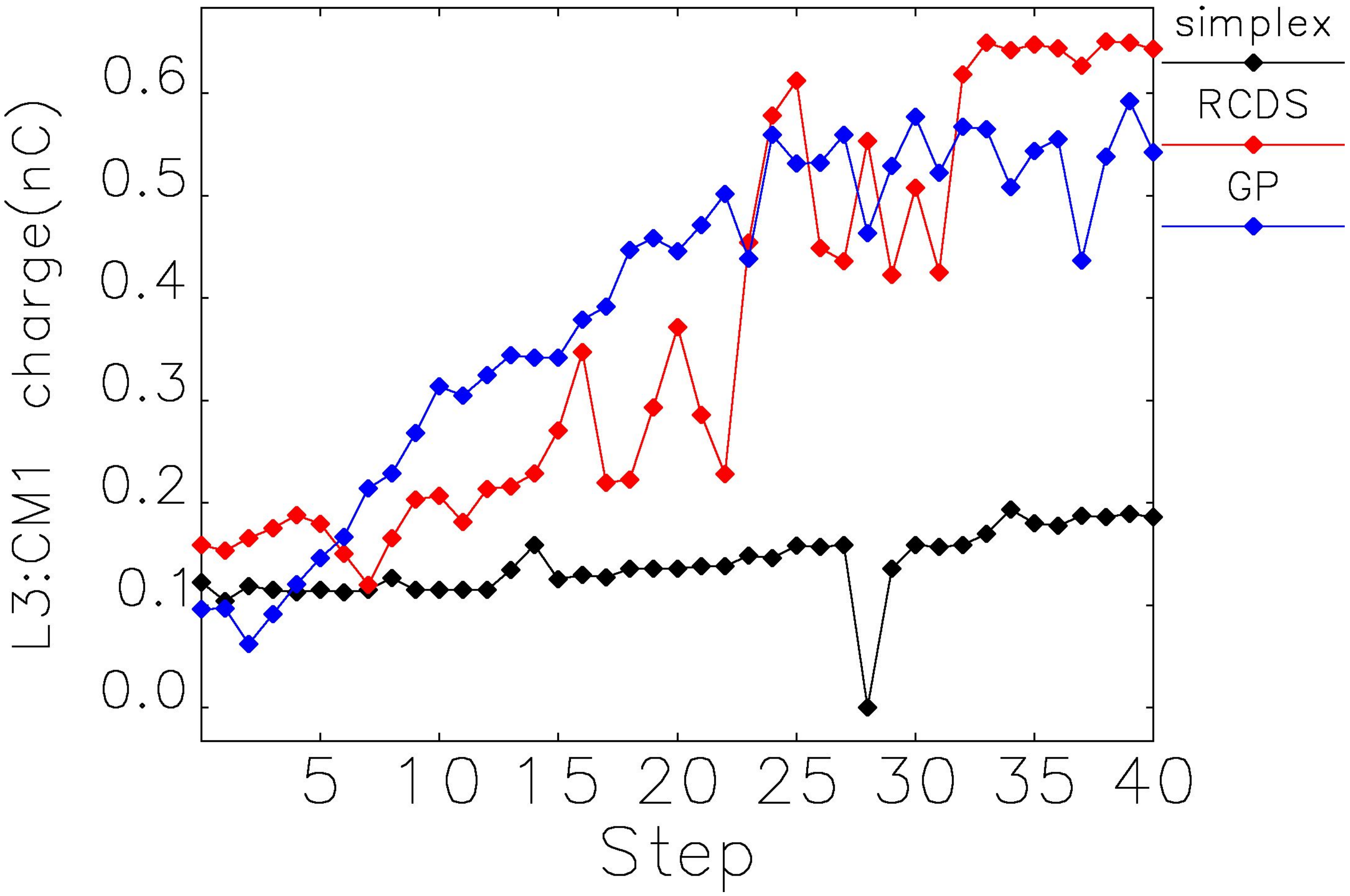
Left: Npop 20, Step 15%
Middel: Npop 12, Step 10%
Right: Npop 8, Step 10%

Best step size: 10%



L3:CM1 Charge Optimization with RG2 Gun, 2019
Target > 1.0nC (150mA gun current, 13.6kV kicker voltage)

GP was not able to find solution starting from operational condition



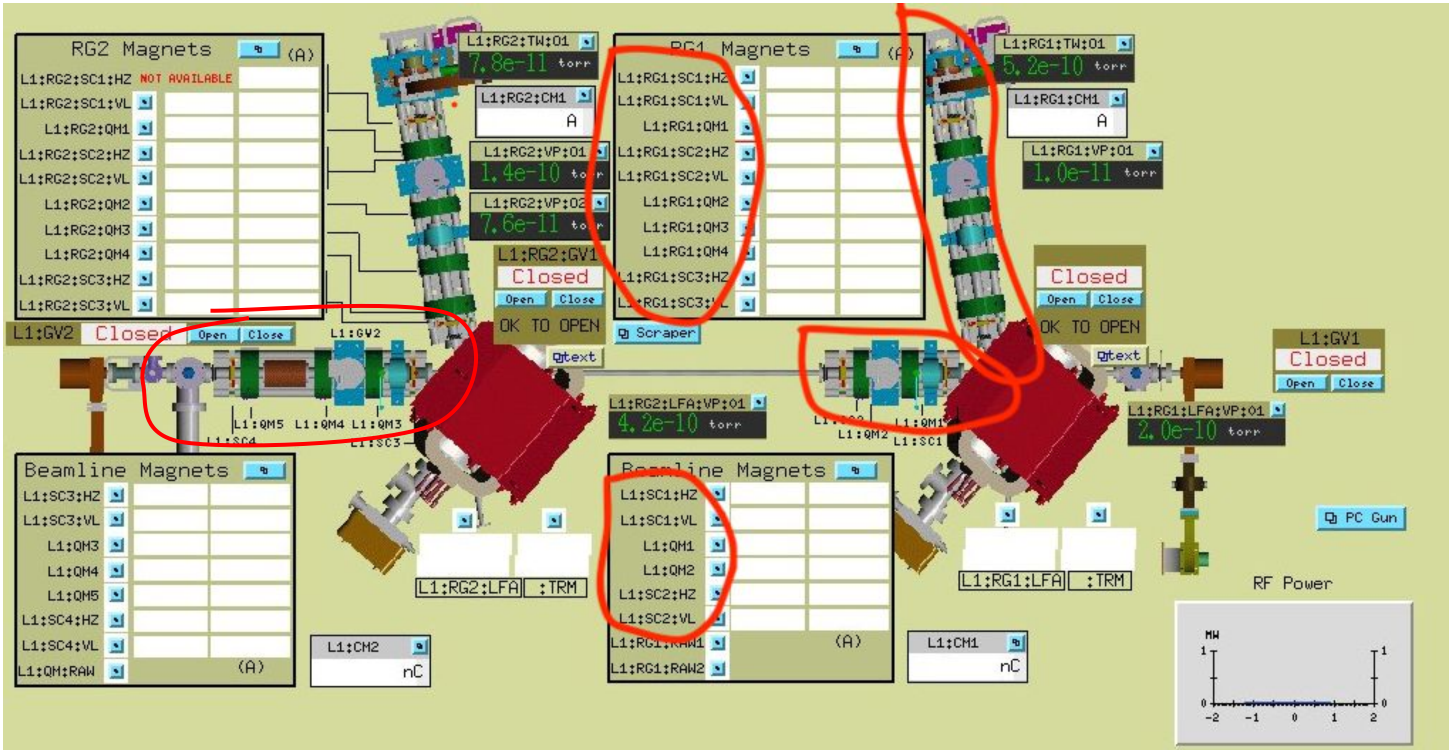
Comparison of MG-GPO and GP Optimizer

From the testing results of L3:CM1 Charge Optimization with RG2 Gun

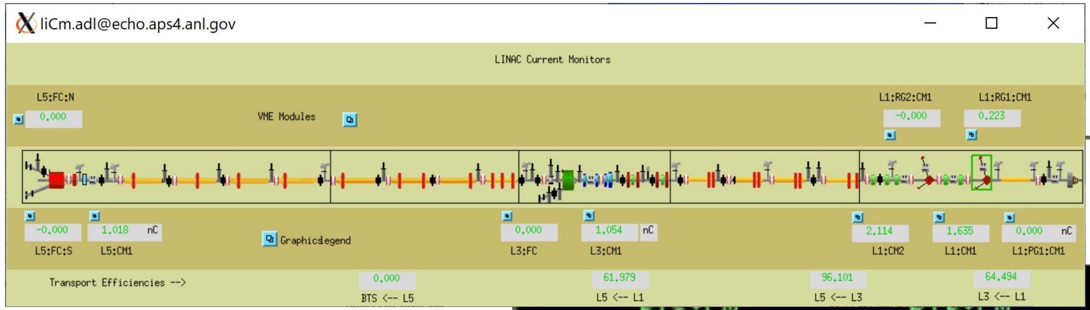
- MG-GPO works well in starting from both good and bad initial conditions
- GP optimizer did not work for this application starting from good condition
- MG-GPO based on MOGA and GP, but more:
    - Mutation and cross-over operations (generating trials) (MOGA)
    - Online hyper parameter optimization (better than GP)
    - Multi-generation (update a population of solutions iteratively)
- MG-GPO v.s Ocelot GP
    - Pros:
        - hyper-parameters obtained online during optimization
        - No raster scan, no offline hyper-parameter fitting (less work)
        - General, apply to most cases
    - Cons:
        - may take longer time than Ocelot GP (model dependent, not successful in our case).

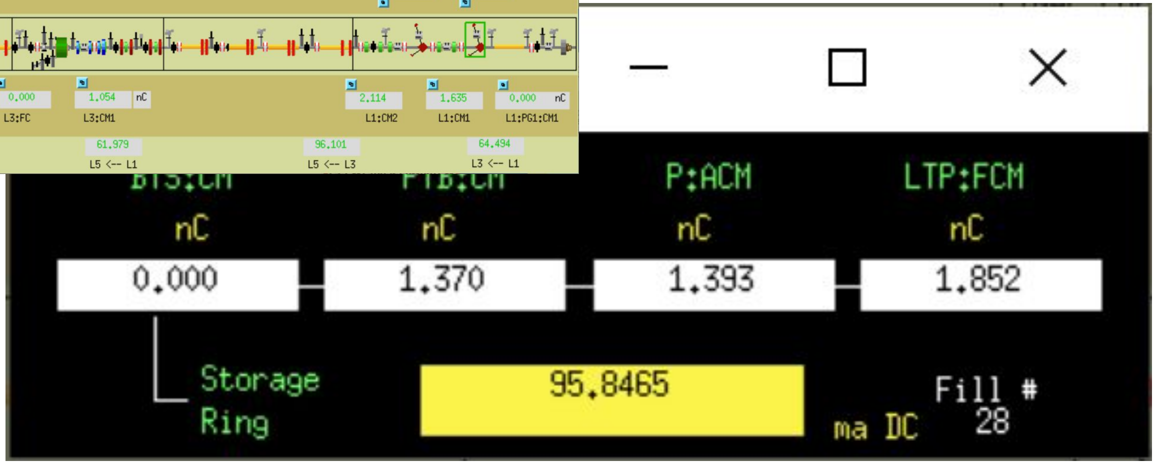
L3:CM1 Charge Optimization with RG1 Gun and MG-GPO

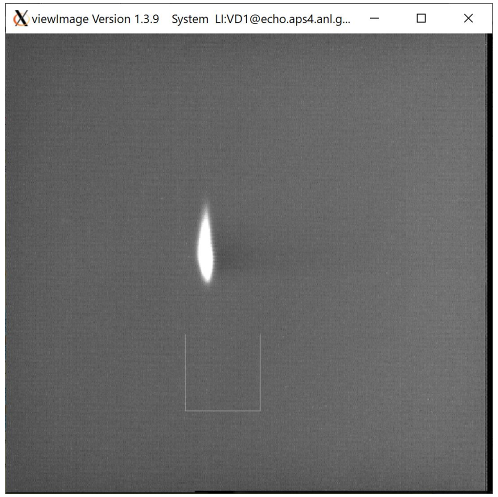
- No good configuration available for RG1
- Starting with 18 input variables: RG1 magnets, L1 magnets (16 total), Alpha Magnet and L1 phase (not successful)
- Removed Alpha Magnet and L1 phase, using 16 input variables (RG1 magnets + L1 magnets)

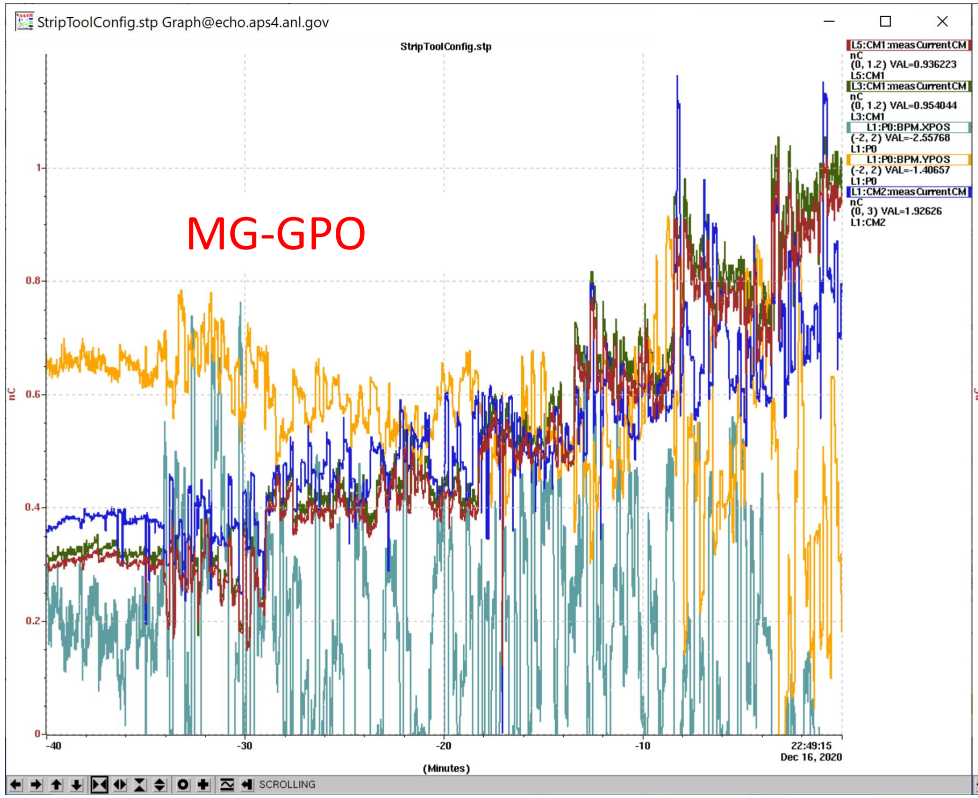


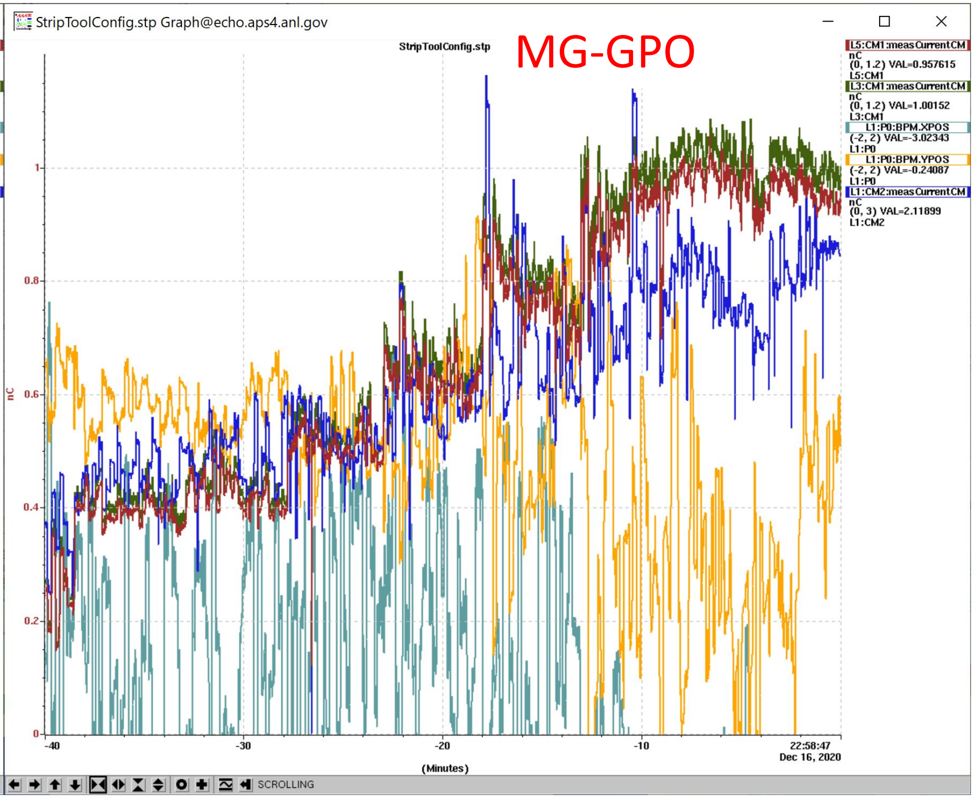
- 10:15 restart MG-GPO with this init condition; on the 9 quads + RG1 SC1 two steering magnets (11 variables); charge improved from 0.4 to over 1 nC at L5:CM1- -success!

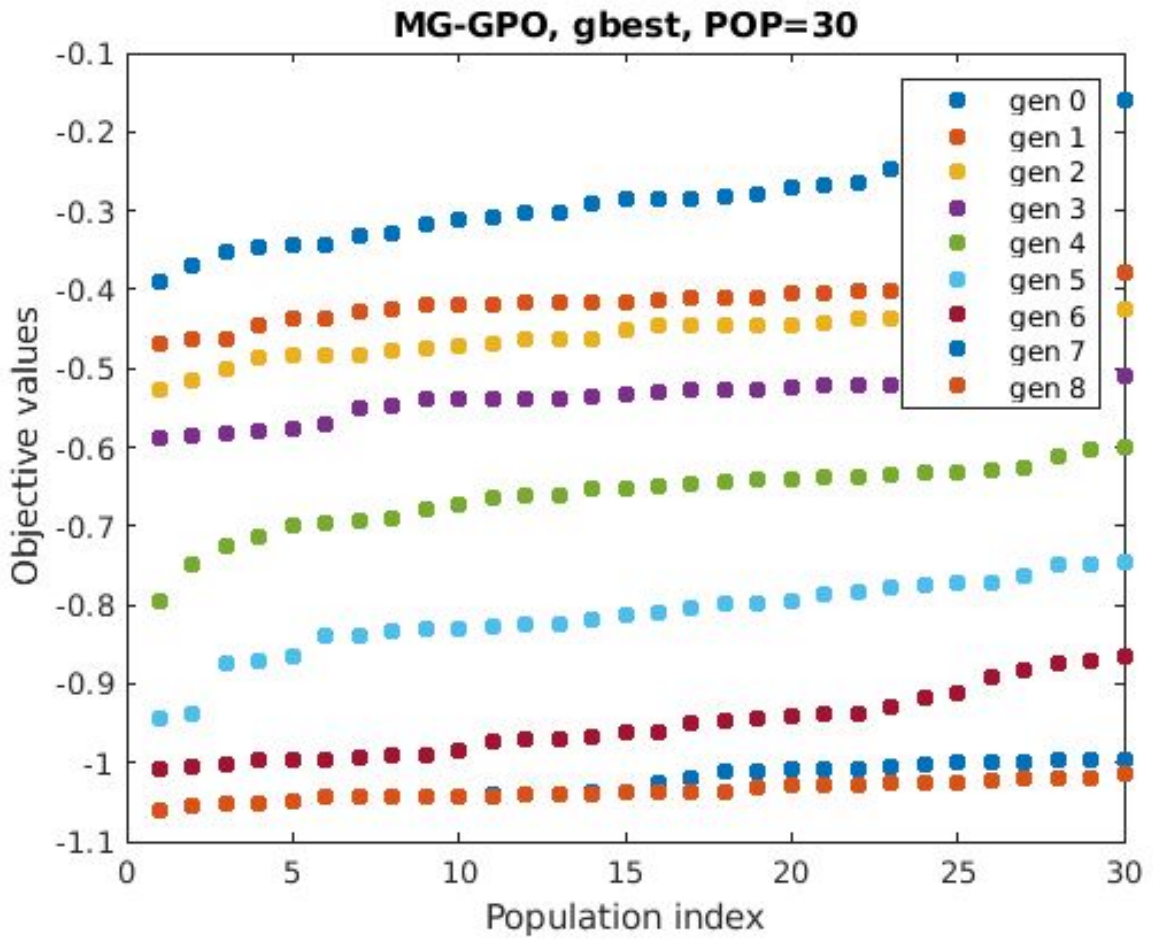


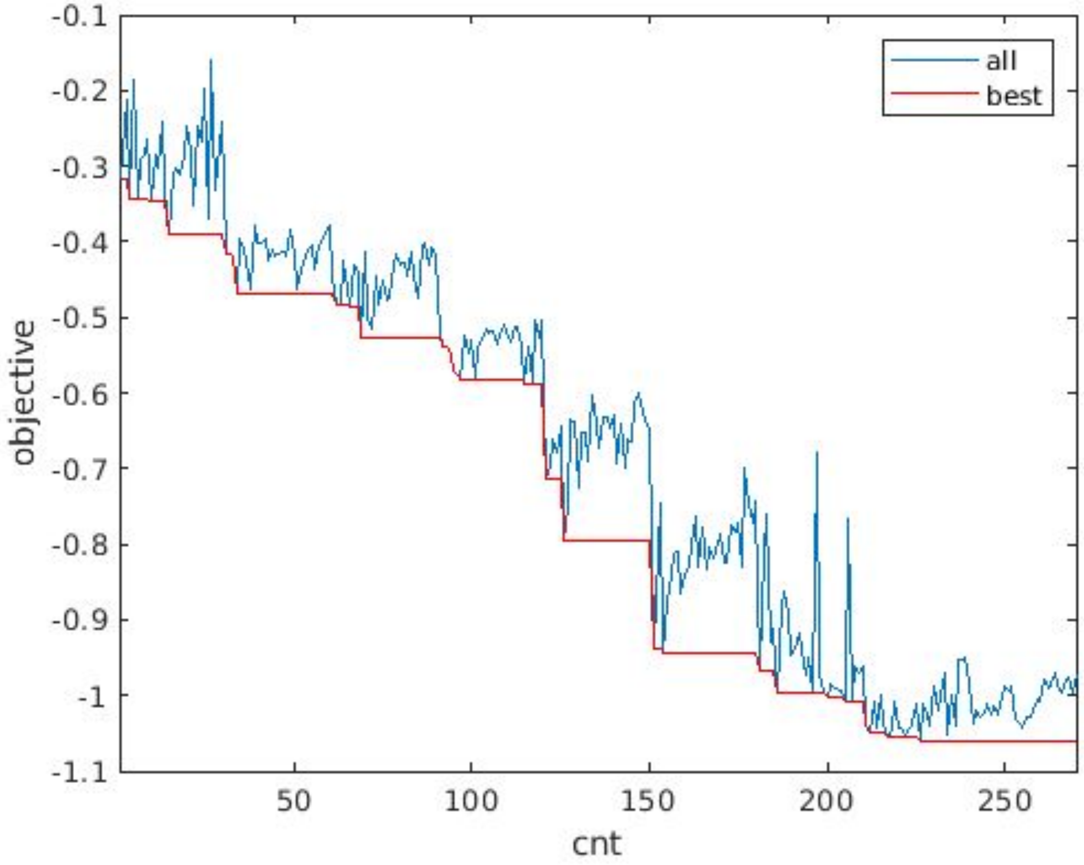












RG1 L3:CM1 charge optimization with MG-GPO, 11 input variables, L1:P0 bpms within 2.5mm (Kicker 13.8kV)

Summary of L3:CM1 Charge Optimization with RG1 Gun

L3:CM1 was optimized to 1.1nC with MG-GPO after following improvements:

- Chose an initial state where L1:P0 is small and there is some L3:CM1 charge (0.3nC)
- Reduced the input variables from 16 to 11:
  - 4 RG1 quads + 2 RG1 SC1 correctors + 5 L1 quads (the most important factors to L1:CM1 charge)
- Added constraints: Limit L1:P0 bpm within 2.5mm (discard the points where L1:P0 bpm is out of the limit), because there are no correctors to correct L1:P0 (modified penalty: if (abs(bpm)>2.5): charge = charge - (abs(bpm)-2.5))
  - Linac beam stability (not stable if L1:P0 is too big)
  - Injection efficiency

Other magnets/correctors are not tuned yet, the L3:CM1 charge and beam quality may be improved after tuning other magnets.

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Summary

- Simplex works well if the initial state is in correct track.
- RCDS improvement:
  - The initial step size was hard-coded as 0.01 (fixed this problem)
  - Use the best solution obtained as start point for each bracketmin and linescan
  - (may be not good, linecan finds the largest decrease direction, should keep it) (trap by local minimum)
- MG-GPO was successful on Linac L3:CM1 charge optimization :
  - RG2 gun: independent of the initial state (bad or good), better results than classic and other ML based optimizers (MOPSO and GP).
  - It was able to obtain good linac beam with RG1 gun from scratch.
  - It also works for SR injection efficiency optimization. (30% - 80 %)

Summary (contin)

- Experience and knowledge (physicists) are important:
  - Input variable choosing: need physicist's knowledge
  - Initial state is important: as in RG1, L1:P0 bpm was small and L3:CM1 charge was 0.3nc in the initial state.
  - Due to the hysteresis problem, step-size factor (0.1) is added to MG-GPO optimizer in this application; the limit the range to +- 0.5 A of the initial state.
  - Parameters tuning:
    - Simplex: initial step size
    - RCDS: noise and initial step size
    - MG-GPO: step size, number of populations in each generation