Lifetime improvement with Particle Swarm Optimization algorithm applied at the MLS and BESSY II

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OUTLINE

- Motivation of lifetime optimization
- Possible methods to optimize lifetime
- Introduction of Particle Swarm Optimization(PSO)
- Experiments
- Conclusion and outlook

BESSY II AND THE MLS

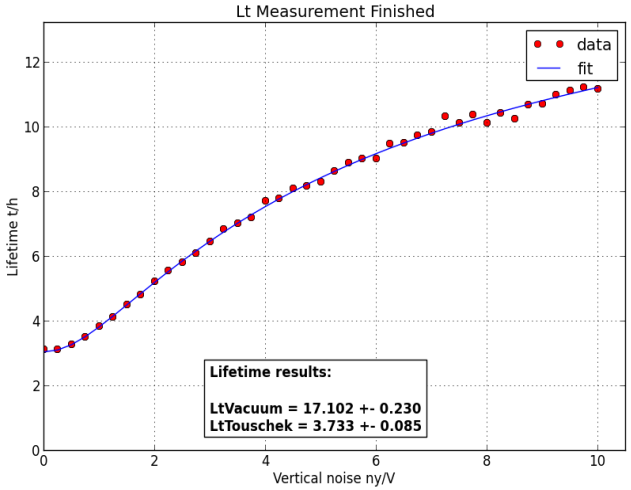
Main Parameters	MLS	BESSY II
Lattice :	**4 DBA**	**16 DBA**
Circumference:	**48 m**	**240 m**
Electron energy:	**630 MeV**	**1.72 GeV**
RF frequency:	**500 MHz**	**500 MHz**
Injection energy:	**105 MeV**	**1.7 GeV(top-up)**
Emittance @ standard user :	**~100 nm rad**	**5 nm rad**
@ low emittance :	**~25 nm rad**	

MOTIVATION

- Low emittance mode of the MLS:
  - Lifetime: 1.5 h @ 150 mA due to small beam size
  - To have even smaller beam size
- BESSY II:
  - Lifetime: 5.7 h /3.7 h @250 mA standard w/o vertical excitation
  - Mandatory for top-up injection
  - Possibility to improve the brilliance
- How?:
  - To adjust the sextupoles to optimize the dynamic aperture

$$\frac{1}{\tau} = \frac{1}{\tau_{touschek}} + \frac{1}{\tau_{gas}}$$

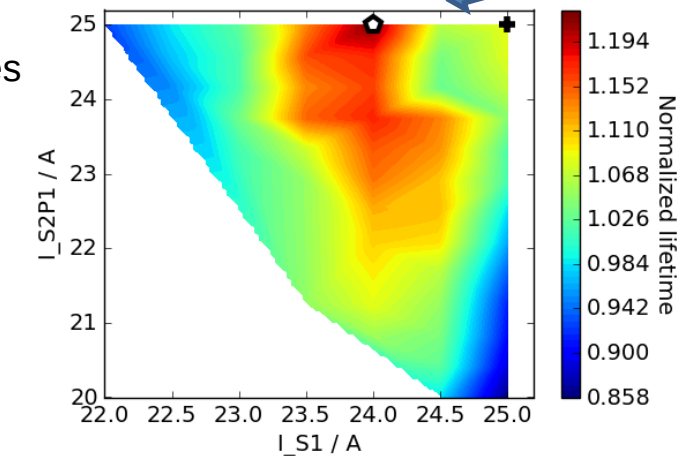
- Why beam-based?:
  - Models hardly agree with machines
- Requirement:
  - Fast, robust, easy to implement

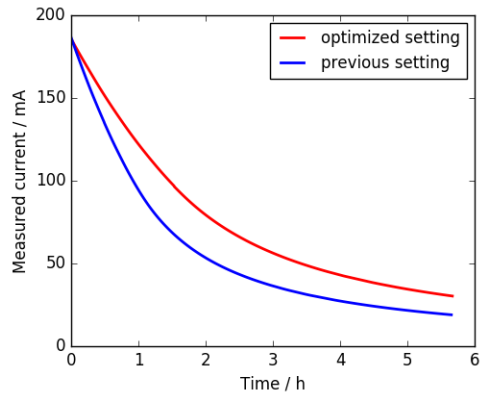


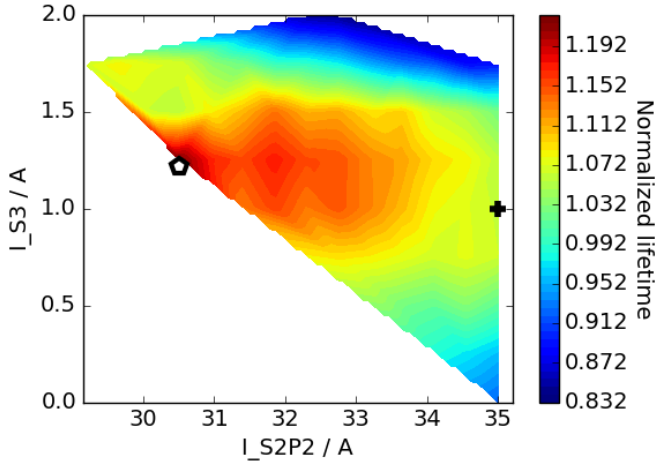
- Manual tuning
  - Local information, requiring skills and deep knowledge of machine
- Global scan: make grids in the N-dimensional space, scan all possible solutions in the grids
  - Suitable: knobs < 4 , slow
  - Overall information: Map
  - MLS : 4 sextupole families

    (details in slide 12)

cross: previous setting
pentagram: optimized setting





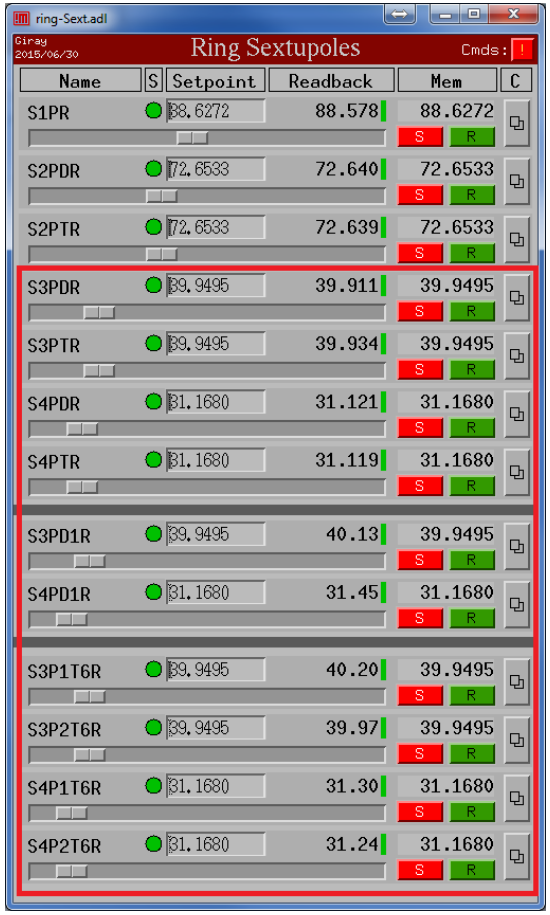


~30% lifetime increase

POSSIBLE METHODS FOR HIGHER DIMMENSIONAL PROBLEMS

How to deal with higher-dimensional problems?

- Numerical optimization methods for fucntions:
  - Noise
  - Efficiency: many iterations
- Robust Conjugate Direction Search(RCDS):
  - Conjugate direction search+Line optimizer
  - X^N problem to X * N problem
  - Noise consideration and outlier deletion
  - Efficient if the initial conjugate direction set is prepared
- Metaheuristic algorithms: genetic algorithm (GA), particle swarm optimization(PSO)



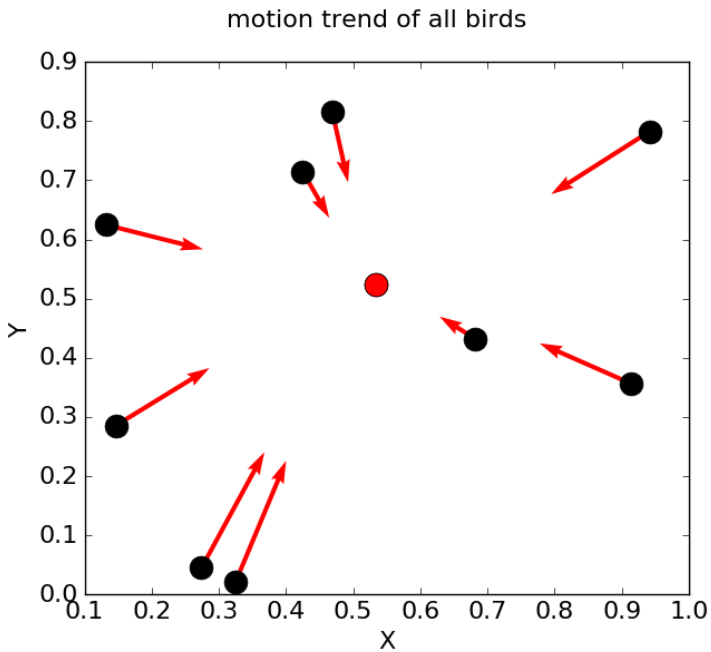
WHY PARTICLE SWARM OPIMIZATION(PSO) IS CHOSEN?

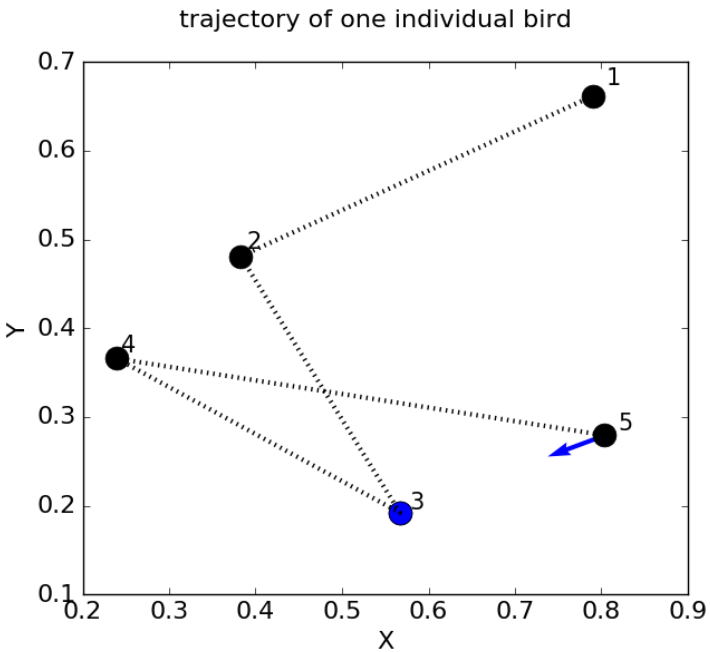
- Paticle Swarm Optimization is a polulation-based optimization method, like GA
  - Initialized with a population of random solutions in the search space
  - Searching for optima by updating population iteratively
- Easy to understand and implement
- Fast convergence*:
  - The program will find a better solution very quickly
- Not sensitive to population size*:
  - Experimental time matters a lot

* Yuhui Shi, Russell Eberhart. Empirical study of particle swarm optimization. Proc. IEEE Congr. Evol. Comput., 1999

WHAT IS PARTICLE SWARM OPTIMATION?

- Developed by Dr. Eberhart and Dr. Kennedy in 1995
  - To simulate the behavior of bird flocking
- Scenario:
  - A group of flying **black** birds searching the only one piece of food in certain space
  - Every bird does not know where the food is
  - The bird closest to the food turns red and can be recognized and replaced by others(gbest)
  - The birds have memory, every bird marks the best position in its flightpath with blue color(pbest)
  - All other birds following the red bird and influenced by the blue positions until the food is found





CORE FORMULAS IN PSO

- How the particles move in the algorithm:
  - Each particle is the bird in the swarm
  - Velocity directing the flight of the particles(where to go and how far)
  - Velocity and position update through Eq. a and Eq. b iteratively

velocity update

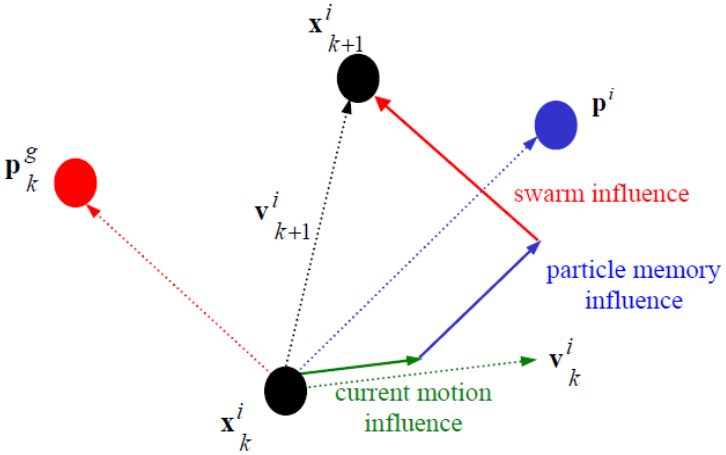
$$v(k+1) = \boxed{w*v(k)} + \boxed{c1*rand()*(pbest - x(k))} + \boxed{c2*rand()*(gbest - x(k))} \quad \text{(a)}$$

$$x(k+1) = x(k) + v(k+1) \quad \text{(b)}$$

position update

w : inertia factor, how much to follow the previous motion
c1 : cognitive factor, leaning from its personal best fitness(pbest) in the memory
c2 : social learning factor, leaning from global best fitness(gbest) in the swarm

w, c1 and c2 should be properly chosen to balance fast convergence and the ability to cover more space in the search

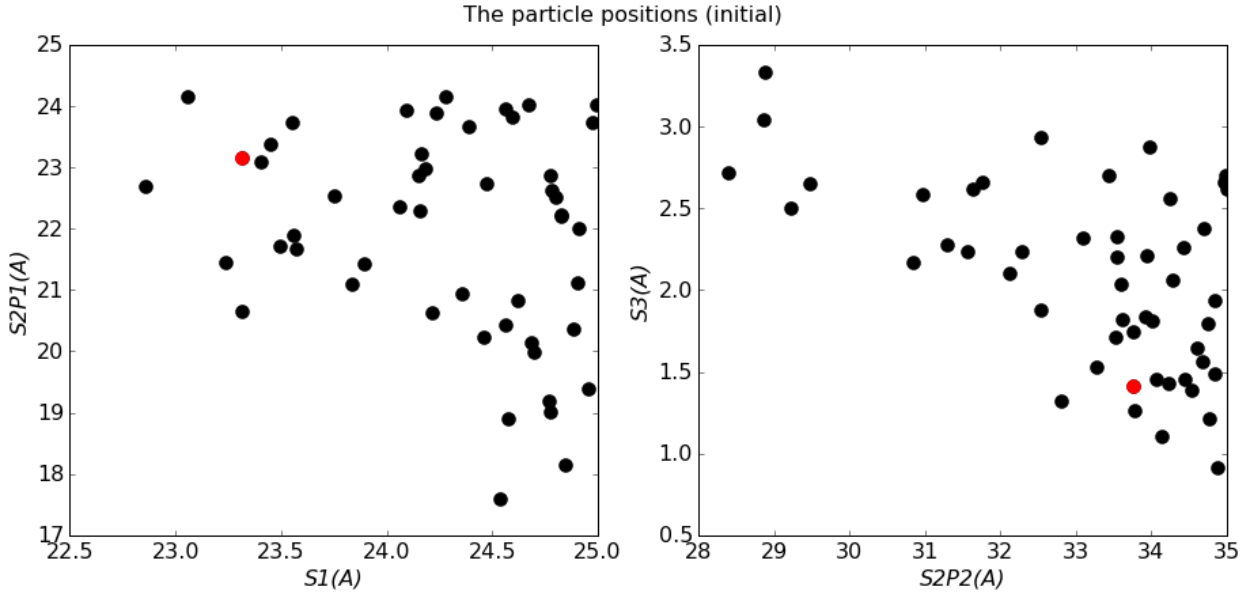


Hassan etc . "A Comparison of Particle Swarm Optimization and the Genetic Algorithm." *American Institute of Aeronautics and Astronautics* (2005)

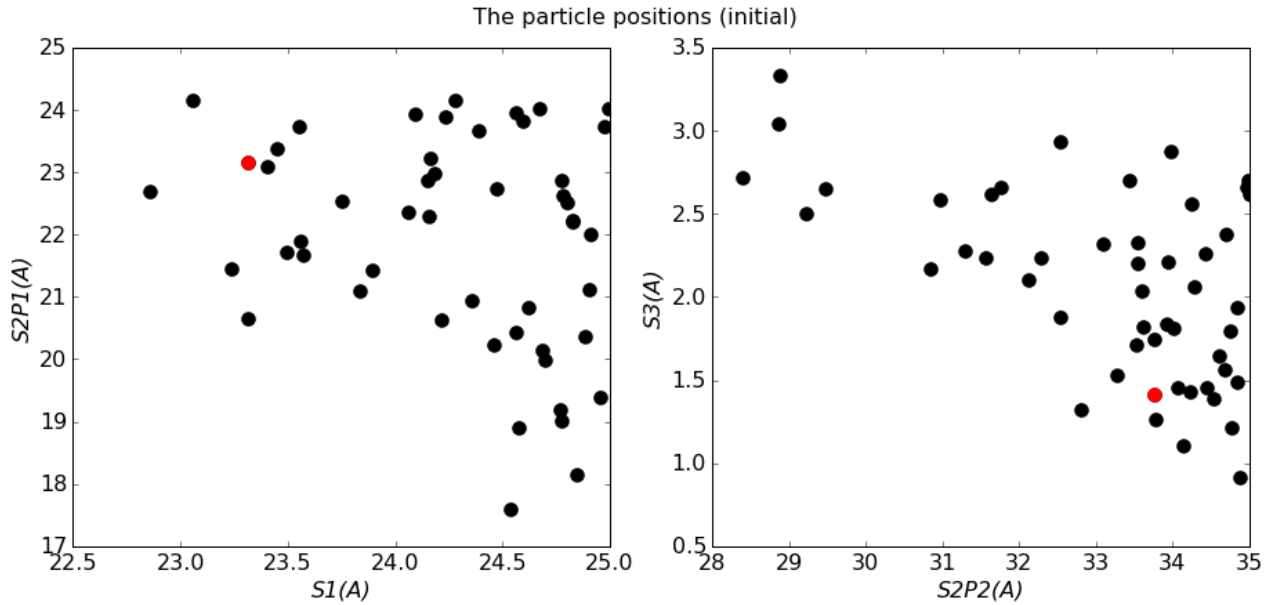
PSEUDO CODE

```
For each particle
   Initialize particle's position, velocity randomly in the search space
   Position: sextupole setting
END

Do
   For each particle
      Calculate fitness value:  Lifetime
      If the fitness value is better than its personal best
          set current value as the new pbest
   End

   Choose the particle with the best fitness value of all as gbest

   For each particle
      Calculate particle velocity according equation (a)
      Update particle position according equation (b)
          to get new sextupole setting
   End
While maximum iterations or minimum error criteria is not attained
```

AN PSO EXAMPLE

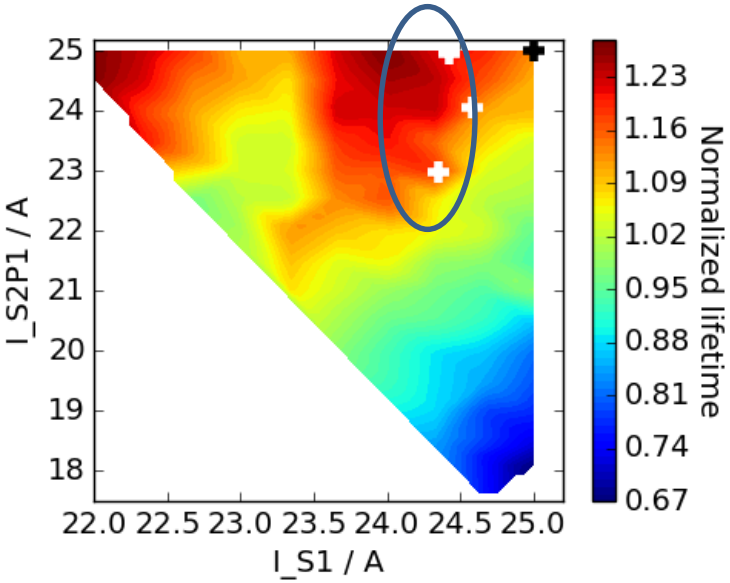


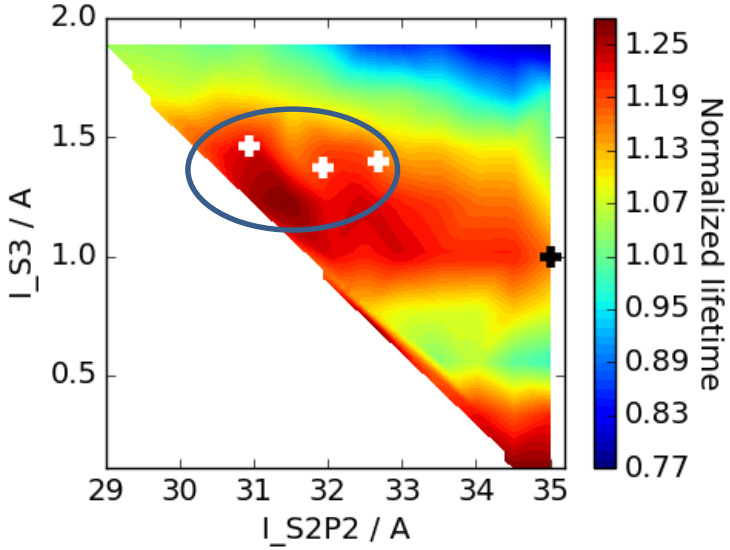
A simulation example



EXPERIMENT AT THE MLS

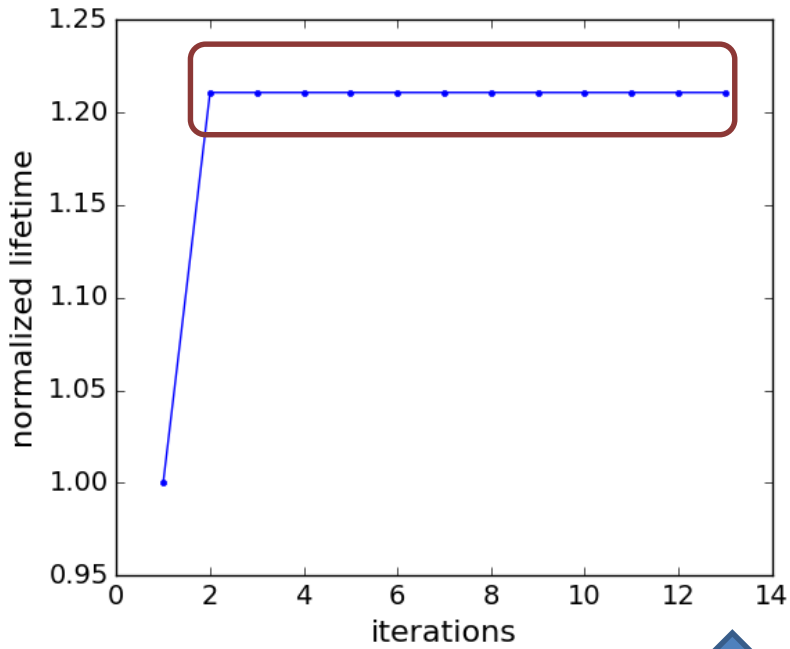
- Variables,fitness and constraint
  - S1, S2P1,S2P2, S3 to vary
  - Single bunch: focus on the touschek effect
  - Fitness value: normalized 1% lifetime
  - Chromaticity : Xi_X>0.15,Xi_X>0.15
- Global scan: 4D
  - stepsize= 0.3 A, 440 solutions in total
  - ~2.5 h scan time: current, step size relevant
  - Black cross: previous setting
- PSO:
  - 15 particles
  - 0.5 h run time for 10-14 iterations
  - White crosses: PSO optimized settings
- Comparison:
  - Global scan provides overall information
  - PSO is faster, but not unique
  - Beam size stable in the optimization

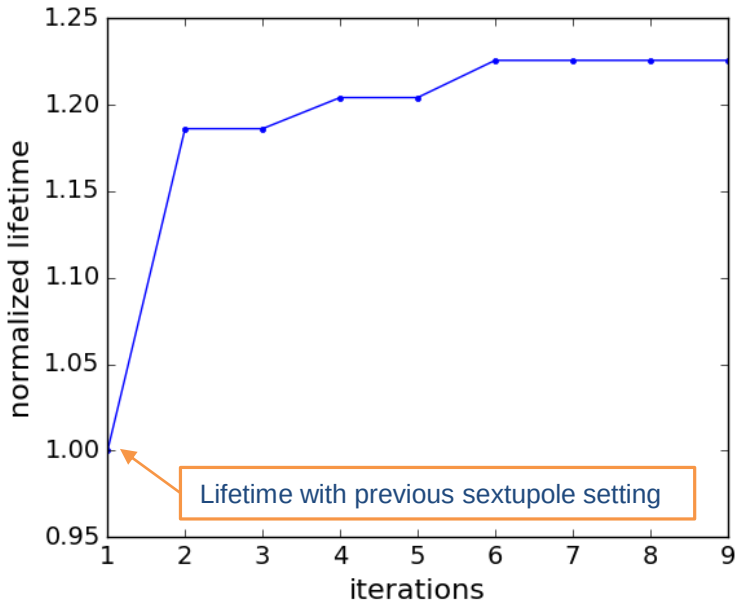


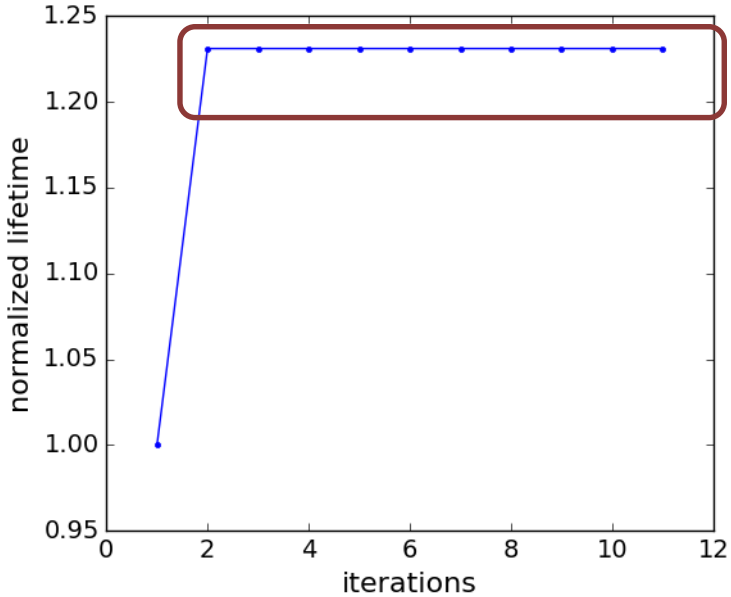


Three runs:

- Maximum 15 iterations:
- >20% lifetime increase achieved

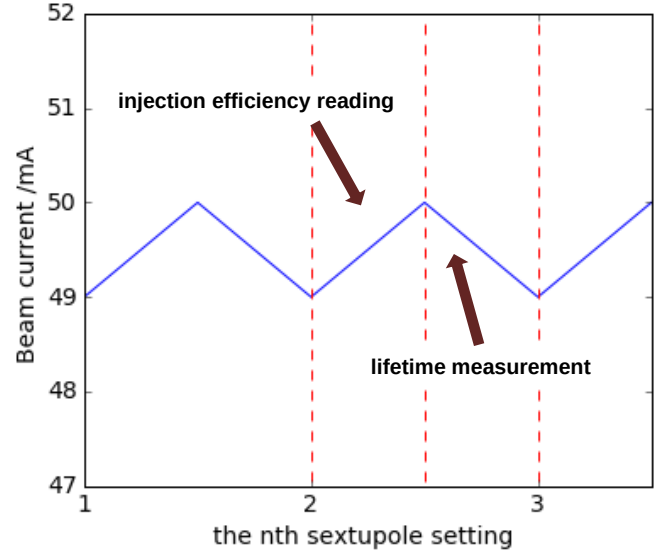


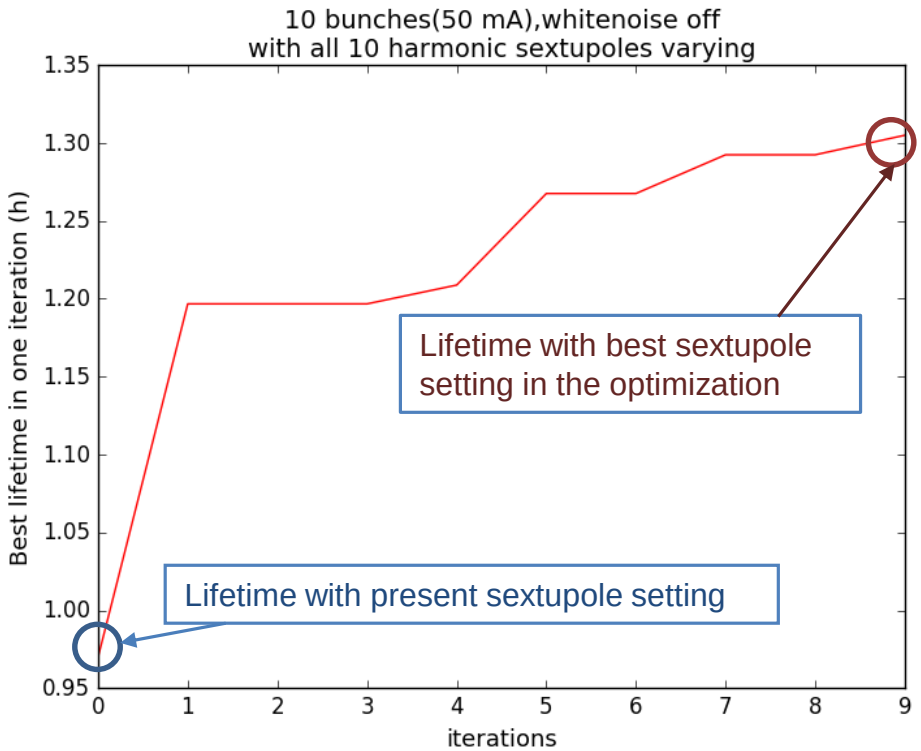




Inertia component plays the major role, C1 and C2 should be tuned !!

- All 10 harmonic sextupoles: for EMIL optics
  - 10 bunches, 50 mA, vertical excitation off
  - Injection efficiency as the contraint: > 90%
  - 49mA to 50mA: injection efficiency average
  - 50mA decaying to 49mA: lifetime measurement
  - 35 particles, 315 settings tried in 9 iterations: ~8h





COMPARISON OF OPTIMIZED AND PRESENT SEXTUPOLE SETTINGS AT BESSY II

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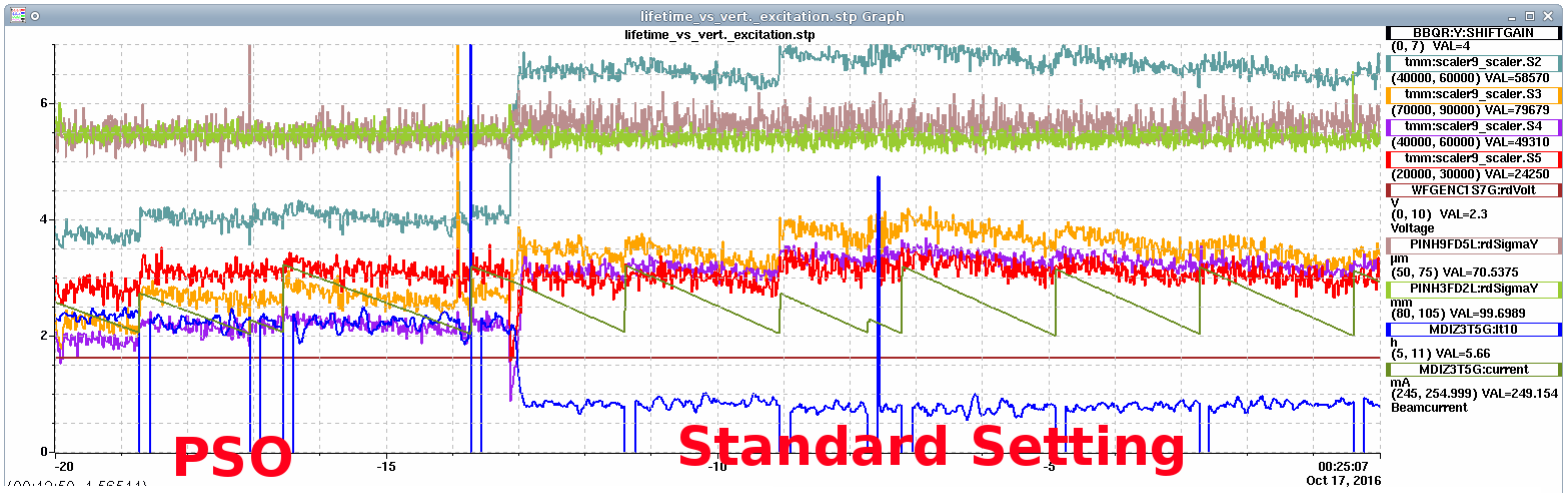
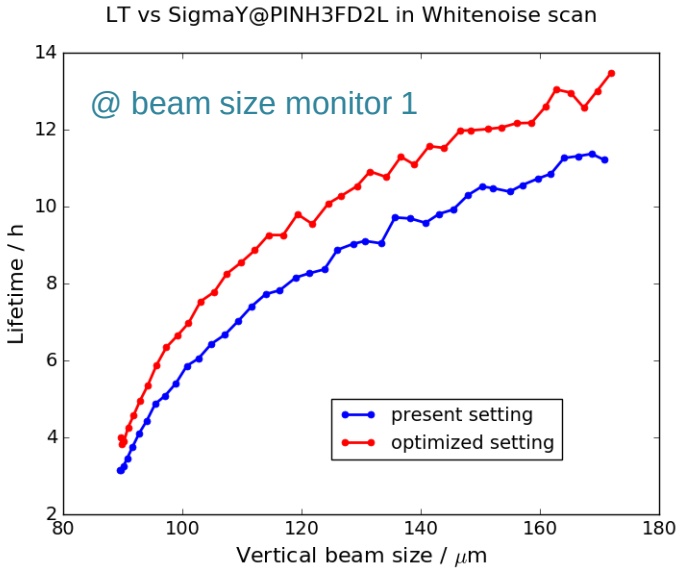
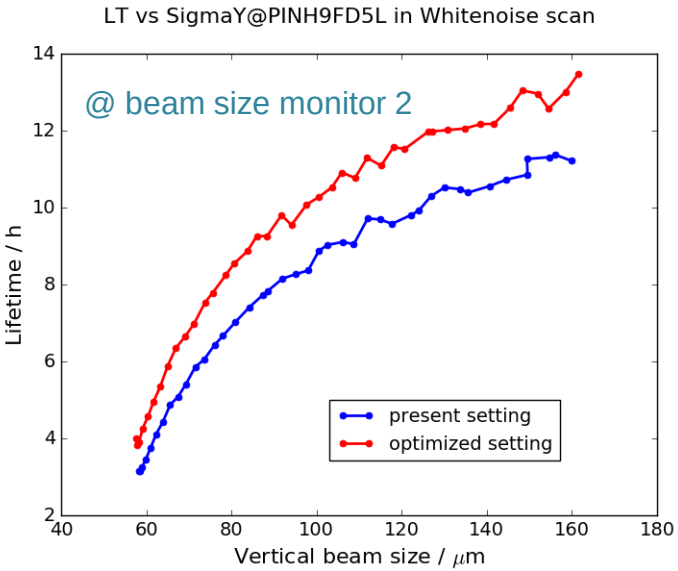
New sextupole setting uploaded in standard user operation

- Lt increase: 21%
- Touschek LT increase: 25%

	LT/h	Touschek LT /h	PINH3 σ_y	PINH9 σ_y
PSO	6.9	4.67	99.5 um	69.5 um
Present	5.7	3.74	99.3 um	69.9 um

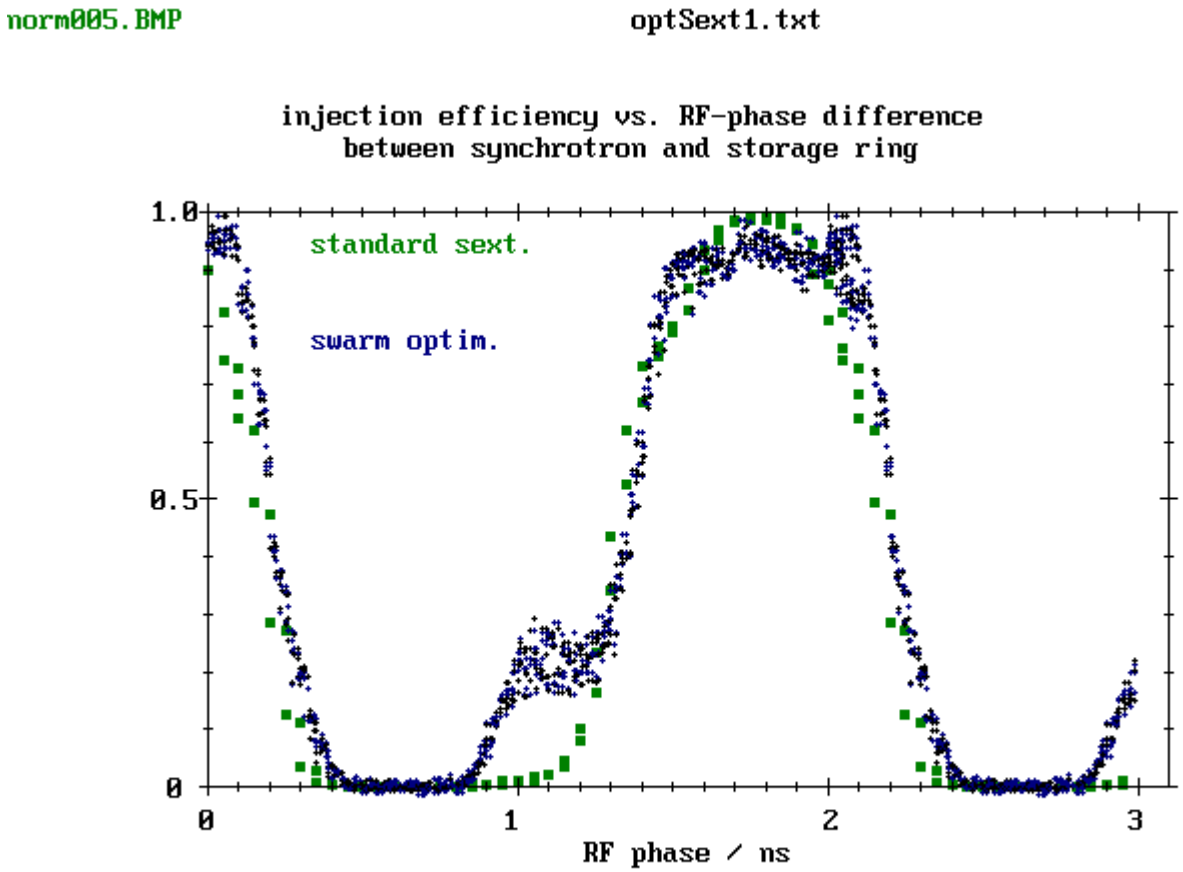






PTB

PHASE ACCEPTANCE AT BESSY II



NOISE PROBLEM

An large outlier in fitness value may lead the particles to wrong direction.

- MLS:
  - statistic error in the measurement: pbest or gbest only update when they are larger than the old value at least 3σ, σ:statistic error
  - Error may be introduced in the lifetime normalization
  - Do the measurement in the high current case, larger signal-to-noise ratio
- BESSY:
  - Errors in the injection efficiency reading: good setting maybe filtered
  - 50mA decaying to 49mA makes the statistic error ignorable

CONCLUSION AND OUTLOOL

- PSO is a useful tool:
  - Fast
  - Not unique results, absolute optima may not be found in only a few iterations
- More inverstigations:
  - To study why lifetime is better: resonance driving terms?
  - Improve the PSO efficiency by tuning inertia factor, cognitive factor and social learning factor
- Potential uses:
  - Transfer line(steers,quadrupoles) optimization for injection rate at MLS
  - Decoupling(skews) at BESSY II

Thanks for your attention!

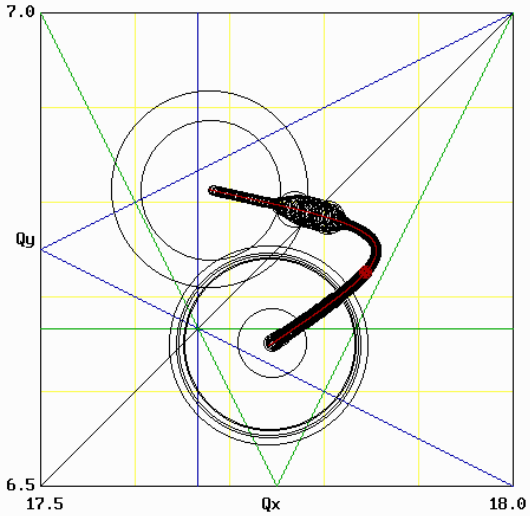
APPENDIX: NEW AND STANDARD SETTING

Comparison of present and optimized setupole settings:

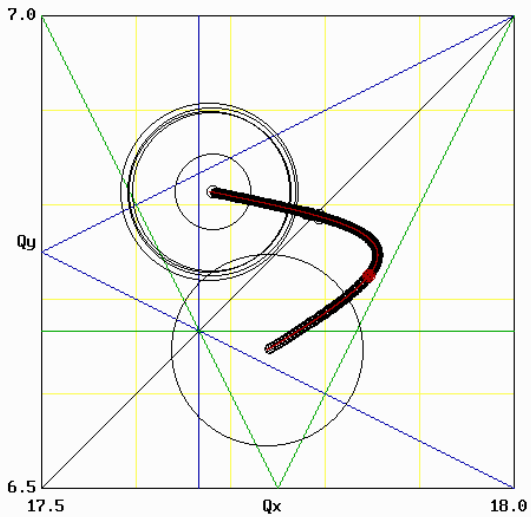
Sextupoles	present	PSO optimized
S3PDR	77	87.36
S3PTR	79.6	75.40
S4PDR	68.4	70.95
S4PTR	100	130
S3PD1R	72	78.36
S4PD1R	48.4	61.29
S3P1T6R	79.6	32.50
S3P2T6R	79.6	30.19
S4P1T6R	75	58.33
S4P2T6R	75	69.33

APPENDIX: MANUALLY TUNING THE SEXTUPOLES AND SKEWS

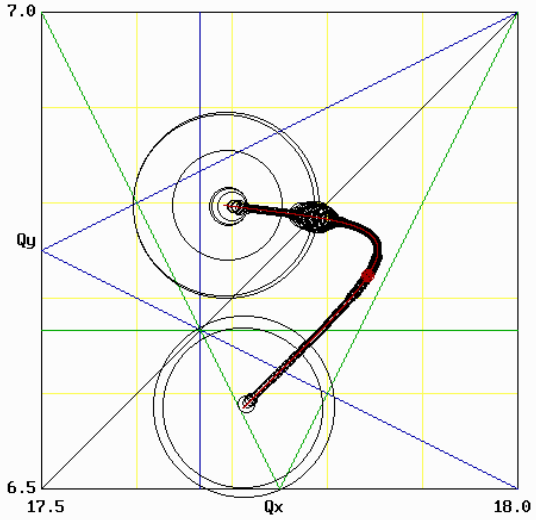
16111300.txt before optimization



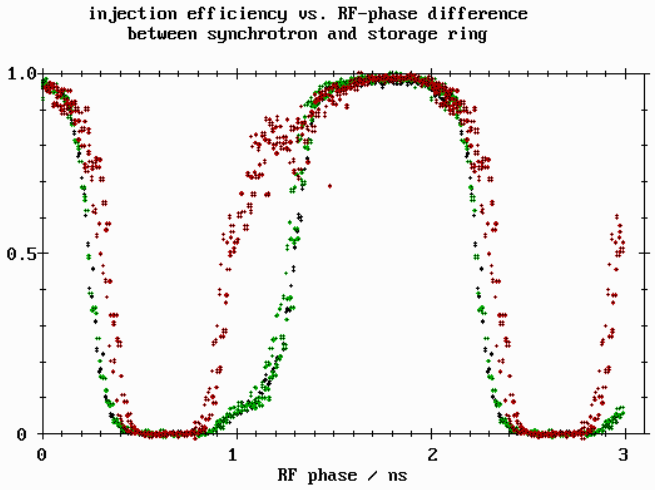
16111301.txt skew Q-optimized



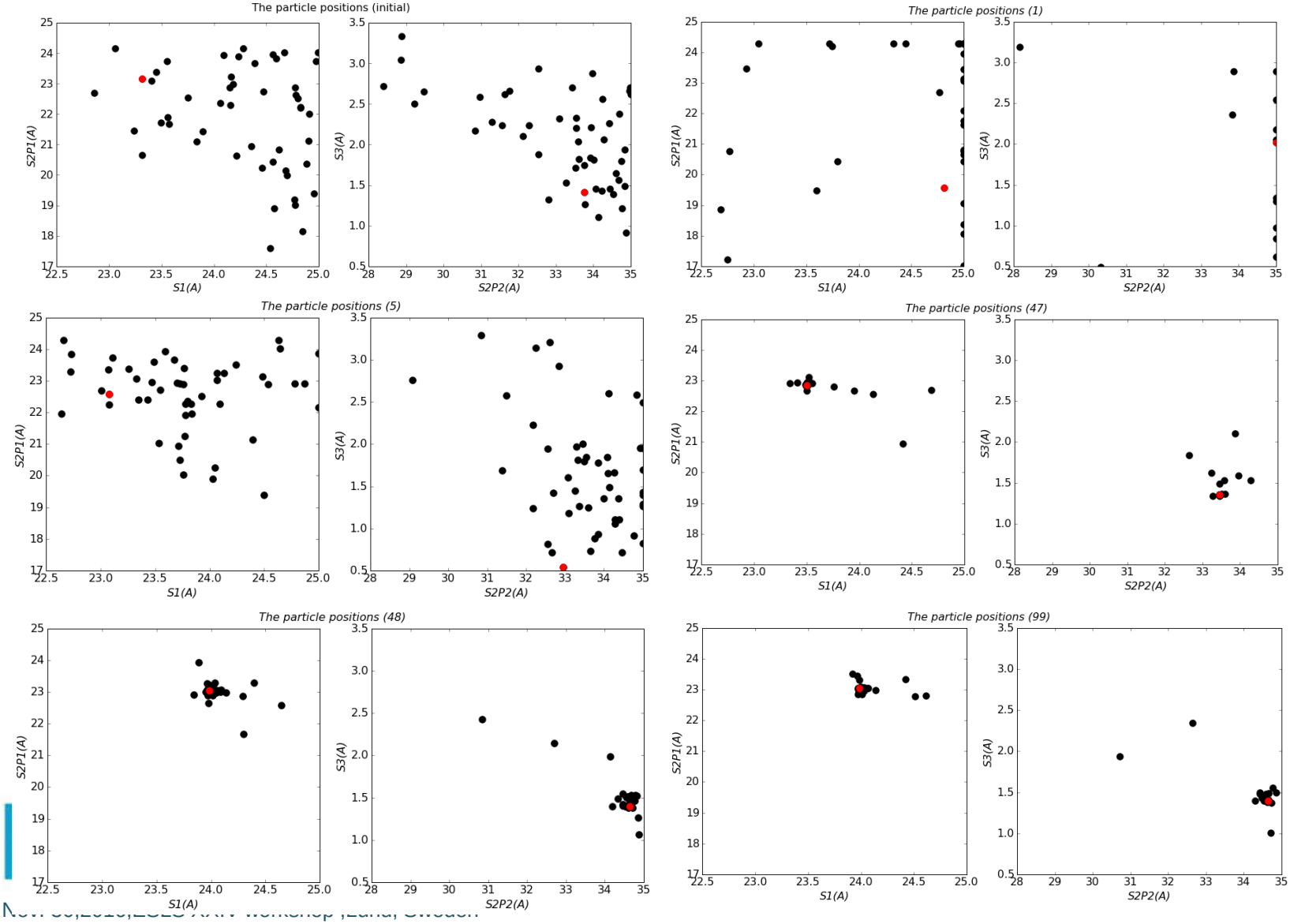
16111302.txt skew Q- and sextupoles optimized



13Nov000.BMP phscan3.txt



APPENDIX: MOTION OF PARTICLES IN PSO



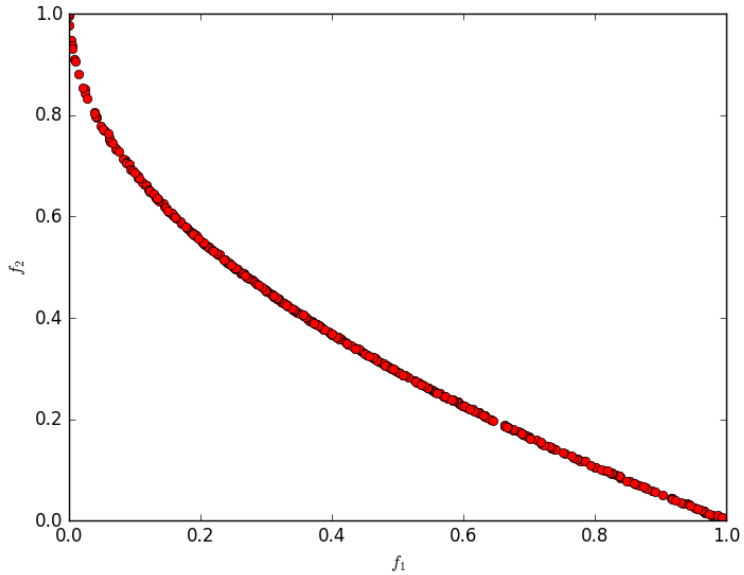
APPENDIX: NON-DOMINATED SOLUTIONS AND PARETO FRONT

A solution x1 is said to dominate another x2,if the conditions are true:

1. The solution x1 is no worse than x2 in all objectives
2. The solution x1 is strictly better than x2 in at least one objective

If any of the above conditions is violated the solution x1 does not dominate the solution x2

If any solution in the set does not dominate x2, then x2 is non-dominated solution



APPENDIX: MOPSO

```
Begin
    Initialize swarm
    Initialize leaders in an external archive
    Sorting(leaders)
    it= 0
    While it < maxit
        For  each particle
            Select leader(gbest)
            Update Position (Flight)
            Mutation
            Evaluation
            Update pbest
        EndFor
        Update leaders in the external archive
        Sorting(leaders)
        it++
    EndWhile
    Report results in the external archive
End
```