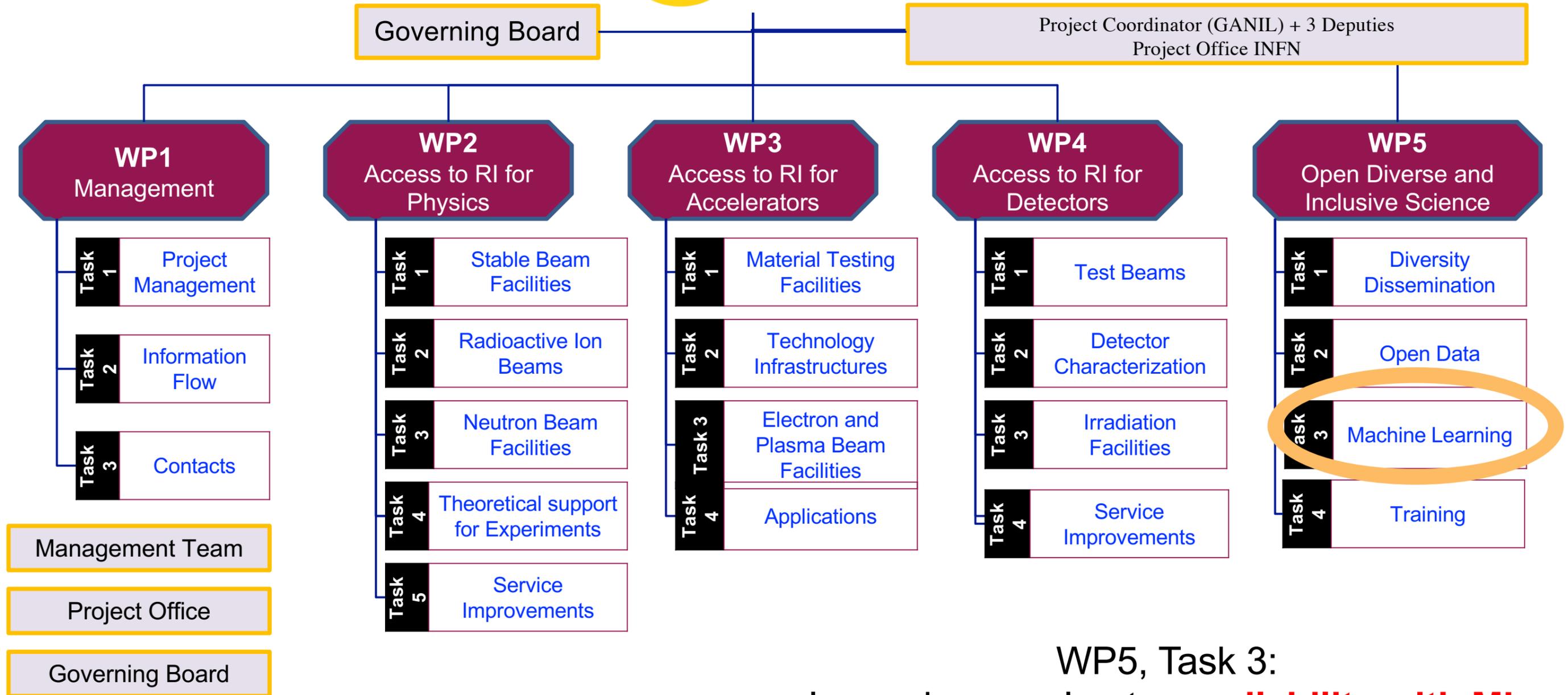


# “Machine learning within the EURO-LABS Network”

Sabrina Appel, Sebastian Rothe





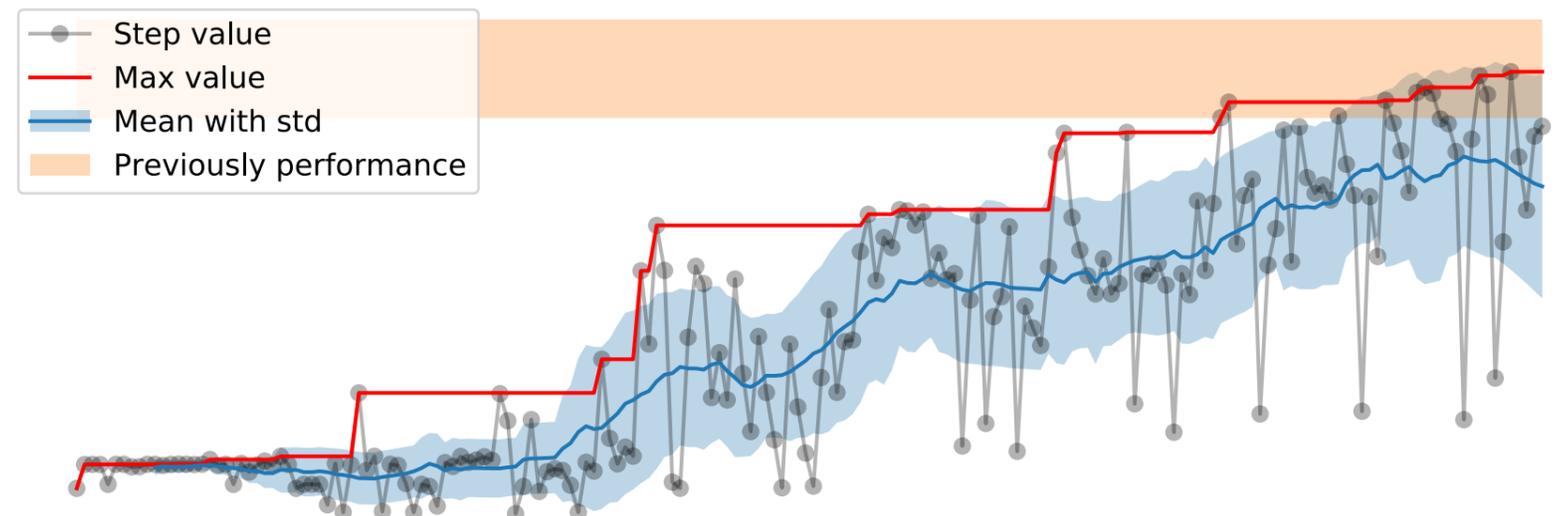
WP5, Task 3:  
Improving accelerator **availability with ML**  
Scientific staff member, E13 position at GSI

**EURO-LABS KOME:**

**KickOff Meeting, Monday 3<sup>rd</sup> afternoon to 5<sup>th</sup> evening October 2022 Bologna, Italy**

- Automated optimization of accelerator means
  - **Reproducibility** or improving beam quality
  - Improving accelerator **availability** (less downtime)
  - High data framework and high quality diagnostics is of large importance
- The aim is to find the optimum framework for **usable ML algorithms** for accelerator problems.
- **Open Data**: Share algorithms and application across facilities
  - Beam optimization algorithms and ML library
- **Virtual access** by extend toolkit to USERS -> link their observables

- **In simulation** evolutionary algorithms can improve beam injection into a Synchrotron and beam line optimization.
- An automatized machine based optimization may improve the time for optimization and control of beam lines as well as improve beam transmission
- First promising online tests with GA have been performed at CRYRING@ESR\* and a transfer line\*\*.



\* S. Appel, et al: International Journal of Modern Physics A Vol. 34, 1942019, (2019)

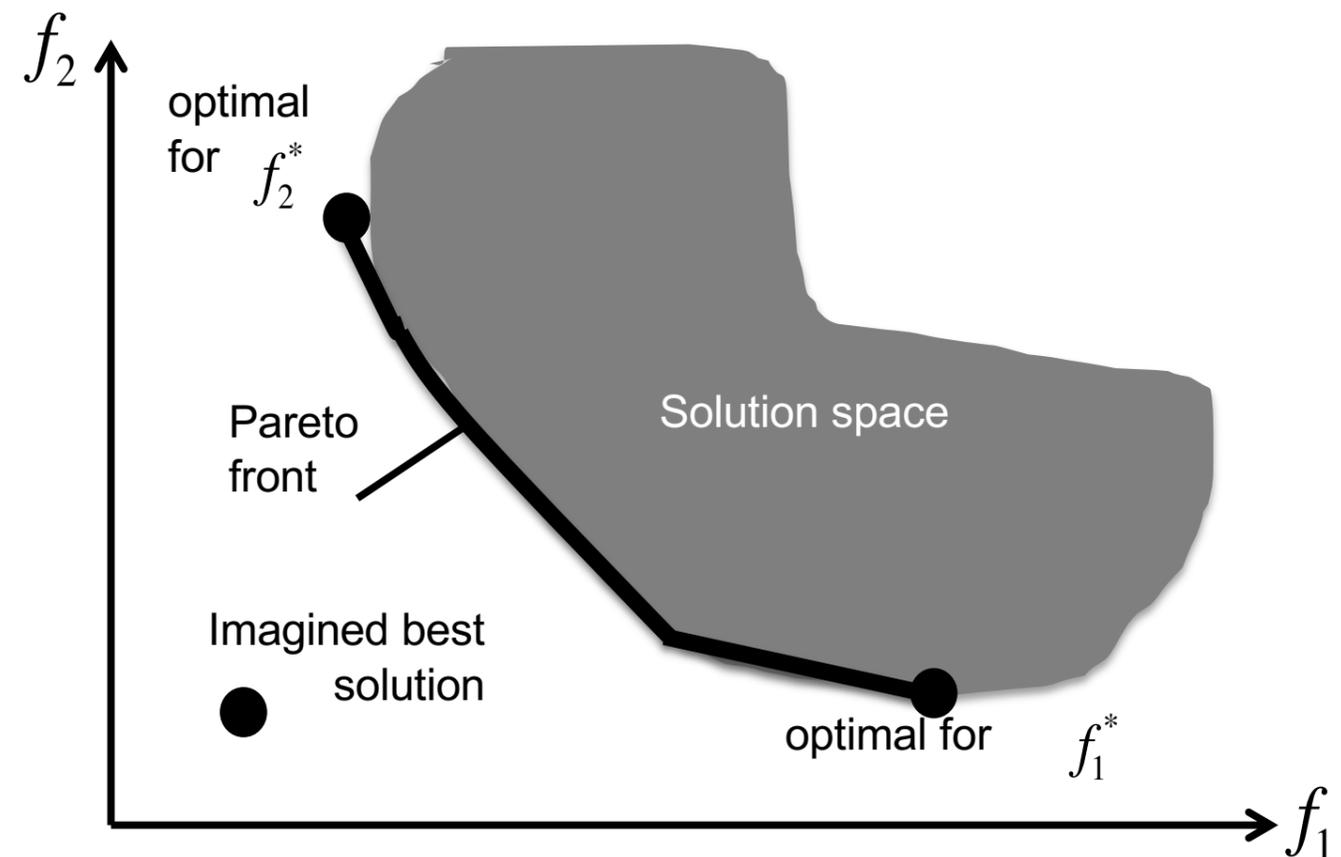
\*\* Stephan Reimann, Dissertation, Goethe Universität Frankfurt am Main (2021)

## General:

The optimization problem is **multi-objective**

$$\min(f_1(x), f_2(x), \dots)$$

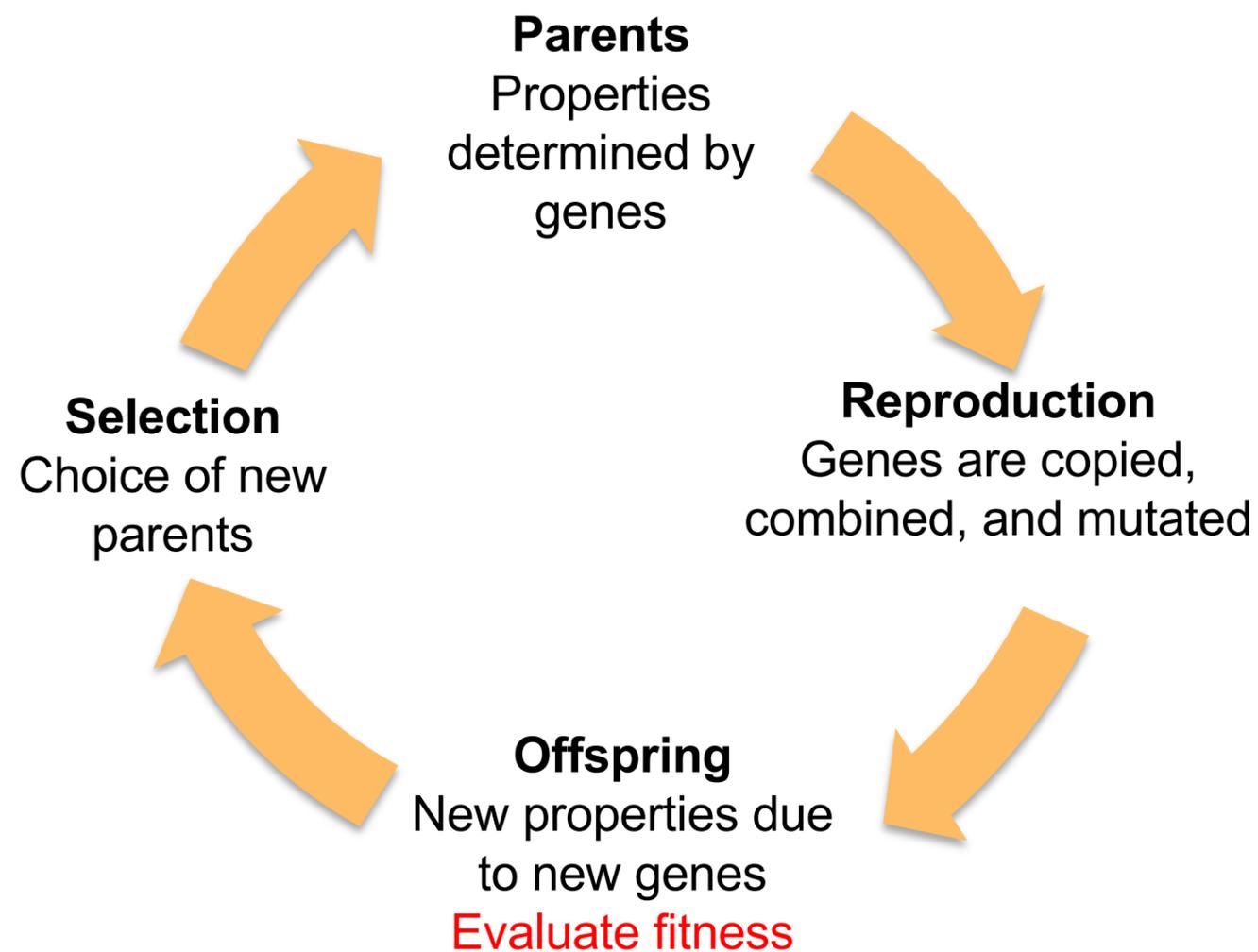
(several criteria to optimize)



- The criteria can be contradicting:  
Improving one criterion means worsening others

➤ Find set of optimal solutions instead of single solution (**Pareto front**)

## Genetic algorithms

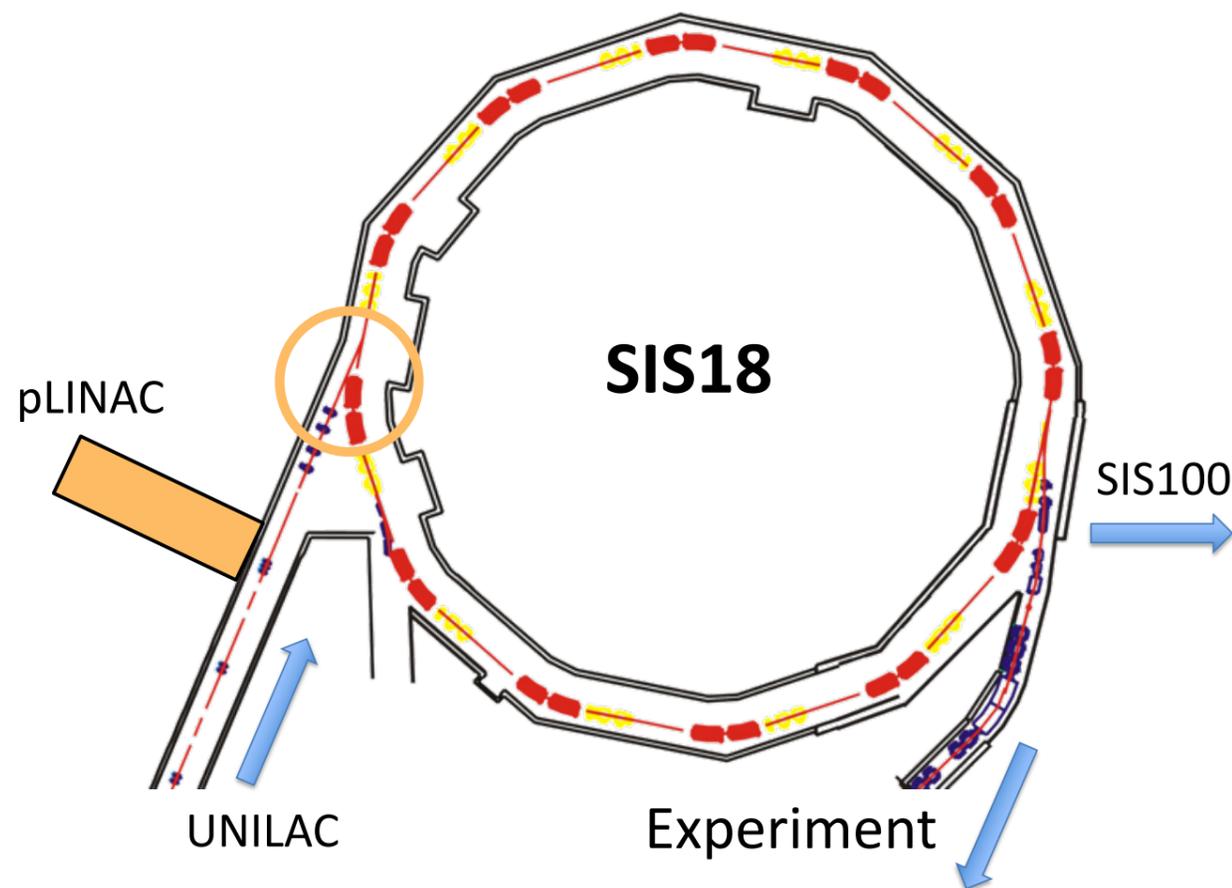


- Nature-inspired algorithms are smart parameter scans:
  - Genetic algorithms
  - Particle swarm algorithms
- Genetic algorithms allow **multi-objective optimization**
- Equally valid solution form a so-called Pareto front (PA front) [4]
- Search for solutions using techniques such as mutation, selection and crossover
- The fitness measures how good an individual is adapted

[4] A. Konak, Reliab. Eng. Syst. Saf., 91 (9), pp. 992--1007, 2006.

# Optimization of injection

Multi-turn injection into SIS18 is one bottleneck to reach intense beams for FAIR.



The loss-induced vacuum degradation is an important key intensity-limiting factor for intermediate charge state ions.

In **simulation** evolutionary algorithms can improve MTI and found a loss-free injection.

Required injector brilliance window could be defined for both SIS18 injectors.

- **Multi-objectives:**

- Gain factor (maximize)  $I = mI_0$
- Beam loss (minimize)  $\eta = \frac{I_{loss}}{nI_0}$
- Emittance  $\epsilon_x$

- **Parameters:**

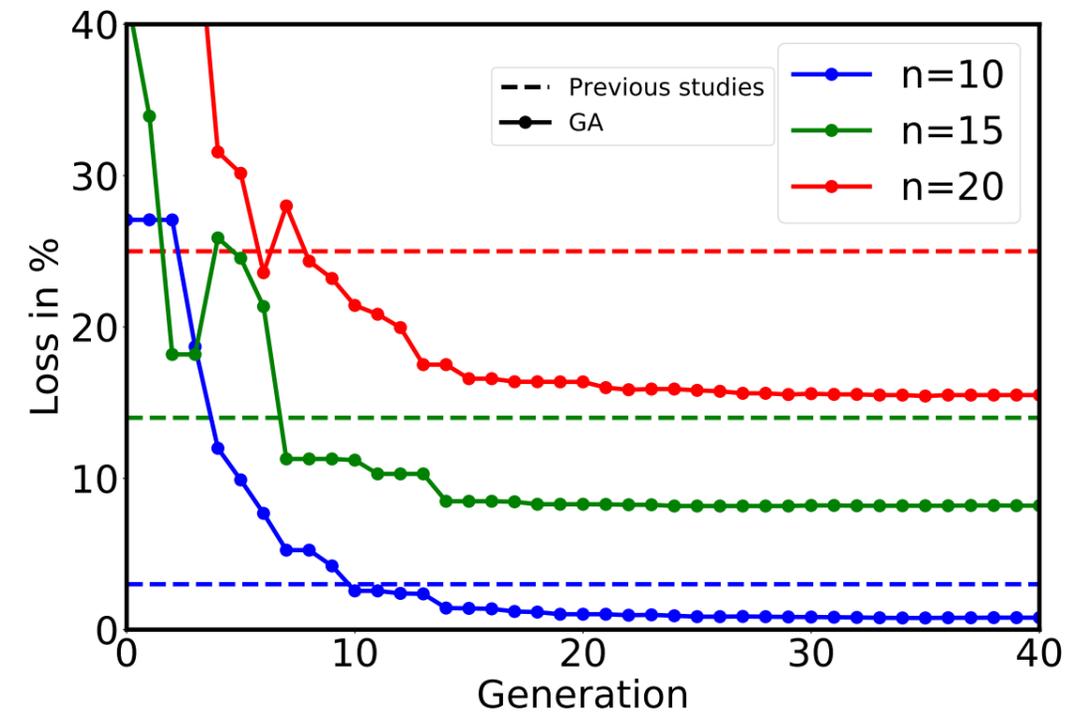
- Position of incoming beam at septum
- Initial bump amplitude and its decreasing
- Injected turns
- Horizontal tune and emittance

# Optimization results

## Optimization of loss

Genetic algorithms can improve MTI.

Especially for **longer** injection GA discovers a much **better** solution.

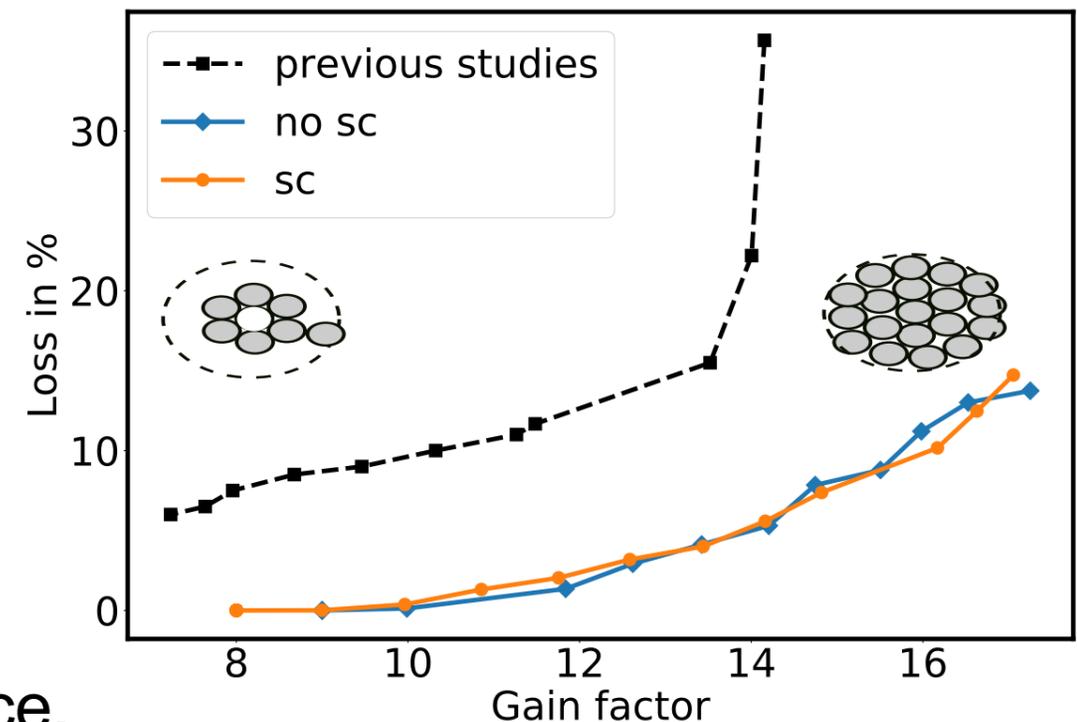


## Optimization of loss and gain factor

Dependence of gain factor on loss.

Loss-free injection could be found.

**Space charge** results in a **similar PA front**, but with different injection settings.



MOPSA shown similar result with faster convergence.

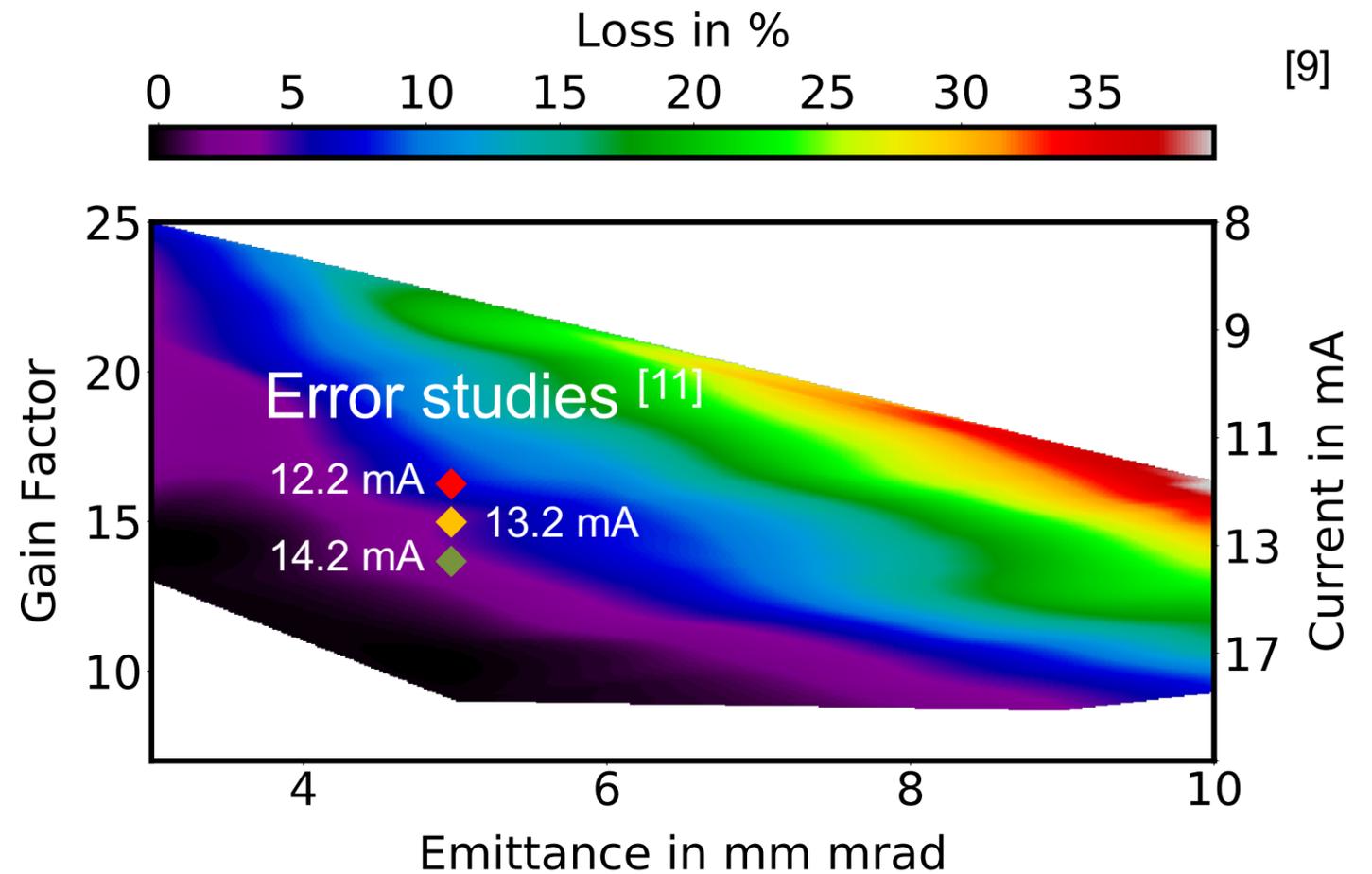
# Optimization results

## Optimization of loss, gain factor and beam emittance (injector)

Dependence of interface parameter

$$B = \frac{I}{\varepsilon} \quad m(\eta) = \frac{N}{I} qf_0$$

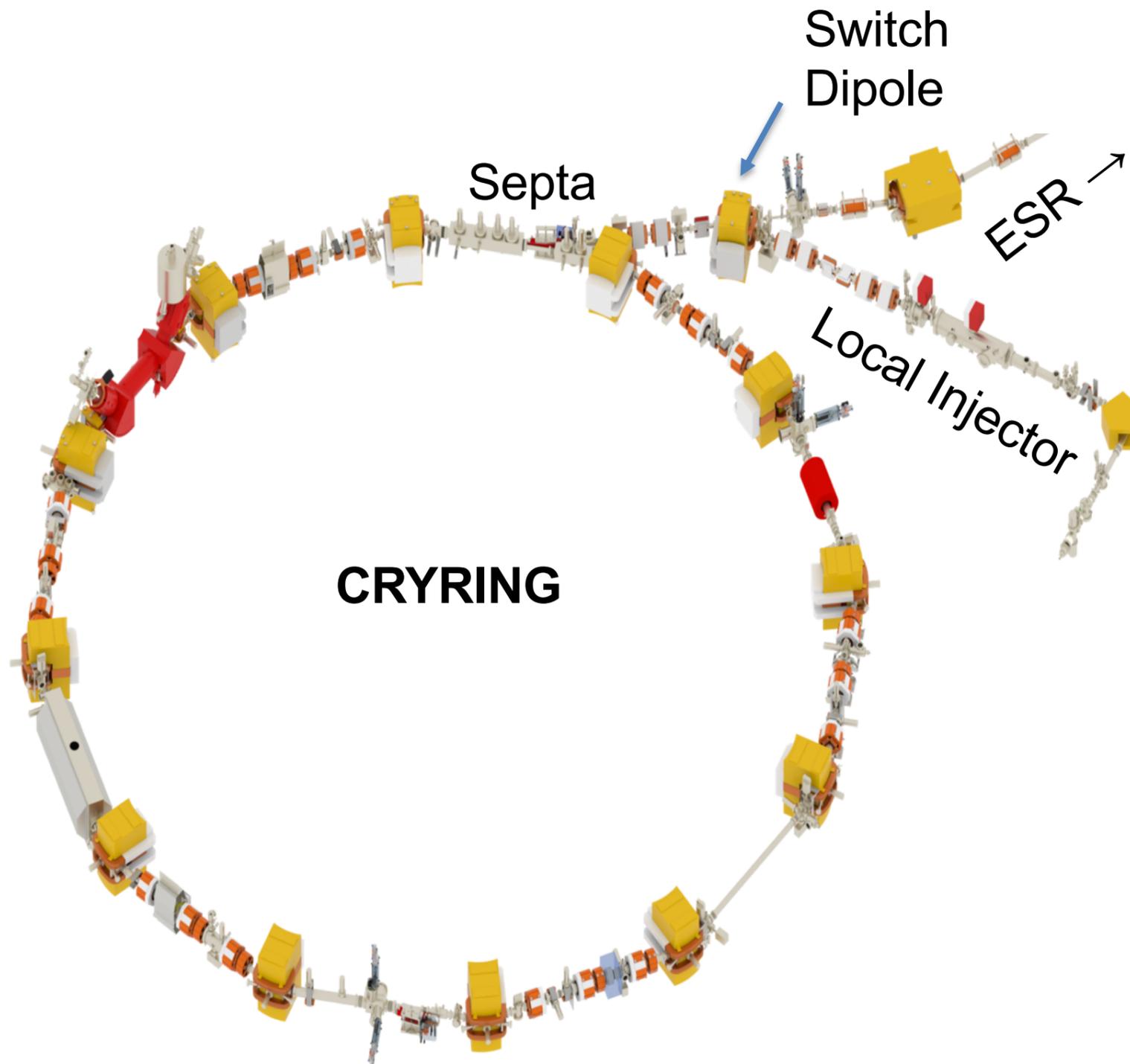
allows to define a frame, in which the required beam parameter can be **matched at best**.



3D Pareto front for proton injector has generated also.  
pLINAC: Relaxed situation, generous beam parameter margin [10]

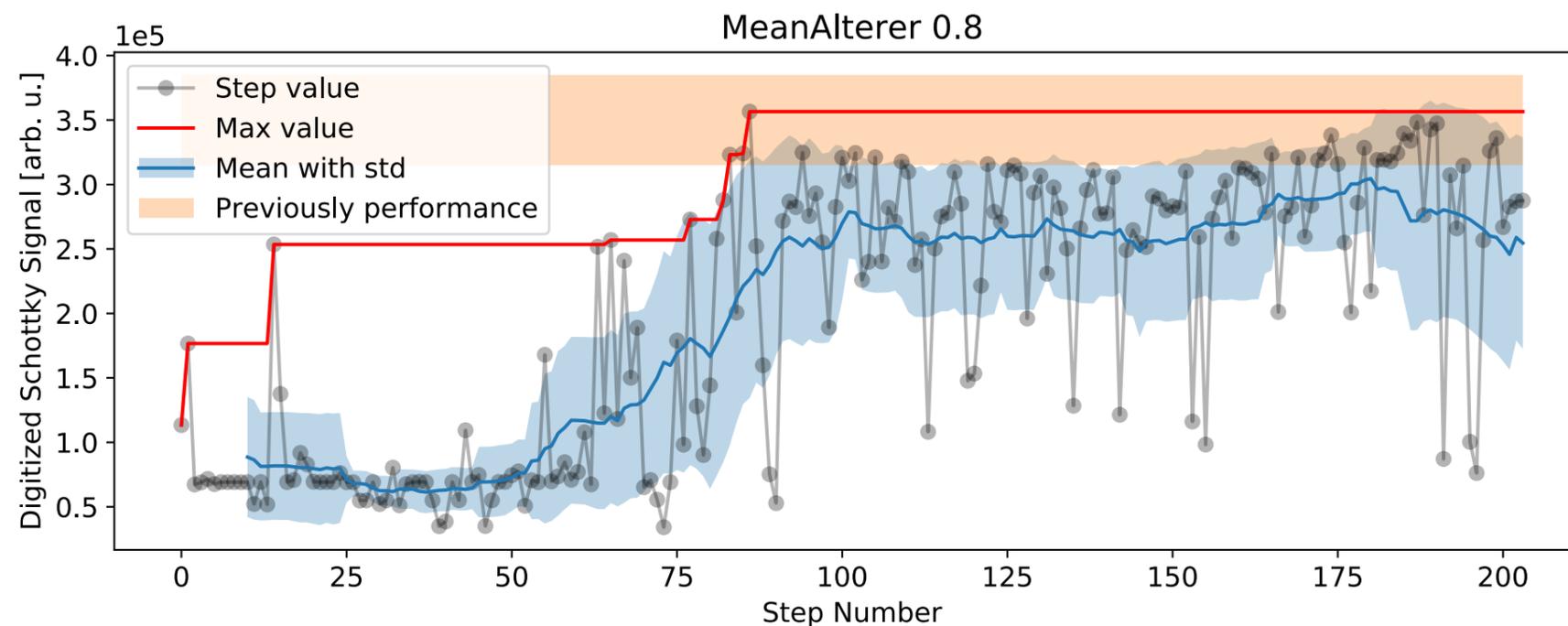
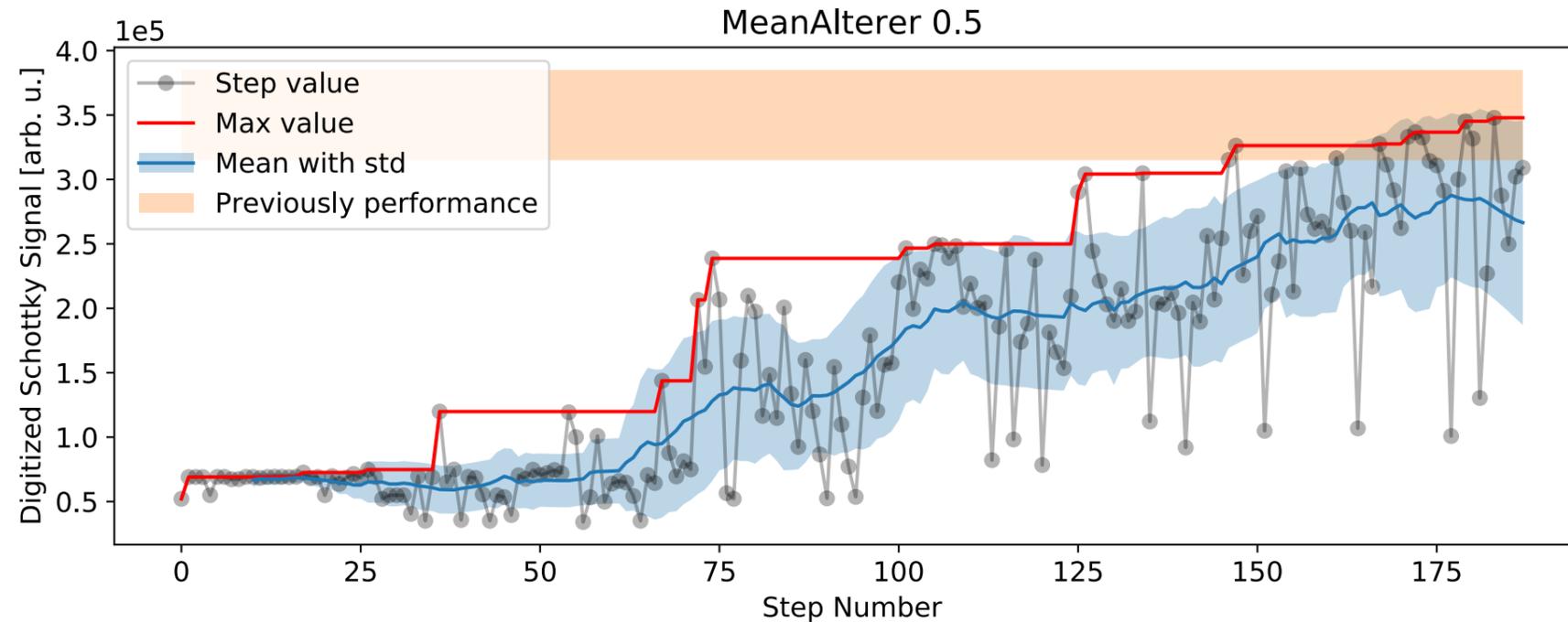
[9] S. Appel et al: Nucl. Instrum. Methods A 852 (2017), pp. 73-79  
[10] C. Kleffner, LINAC2018, THPO046 (2018)

[11] A. Rubin, Beam dynamics design of the new FAIR post-stripper linac, GSI Accelerator Seminar, 14.05.17



- Swedish in-kind contribution to FAIR
- CRYRING@ESR can be used stand-alone for testing novel technical developments.
- Control system is Java based.
- Jenetics end-user ready software library implementing an genetic algorithm in **Java**.
- Choice to use Jenetics was obvious although faster algorithm are known.

# CRYRING@ESR: Online optimization

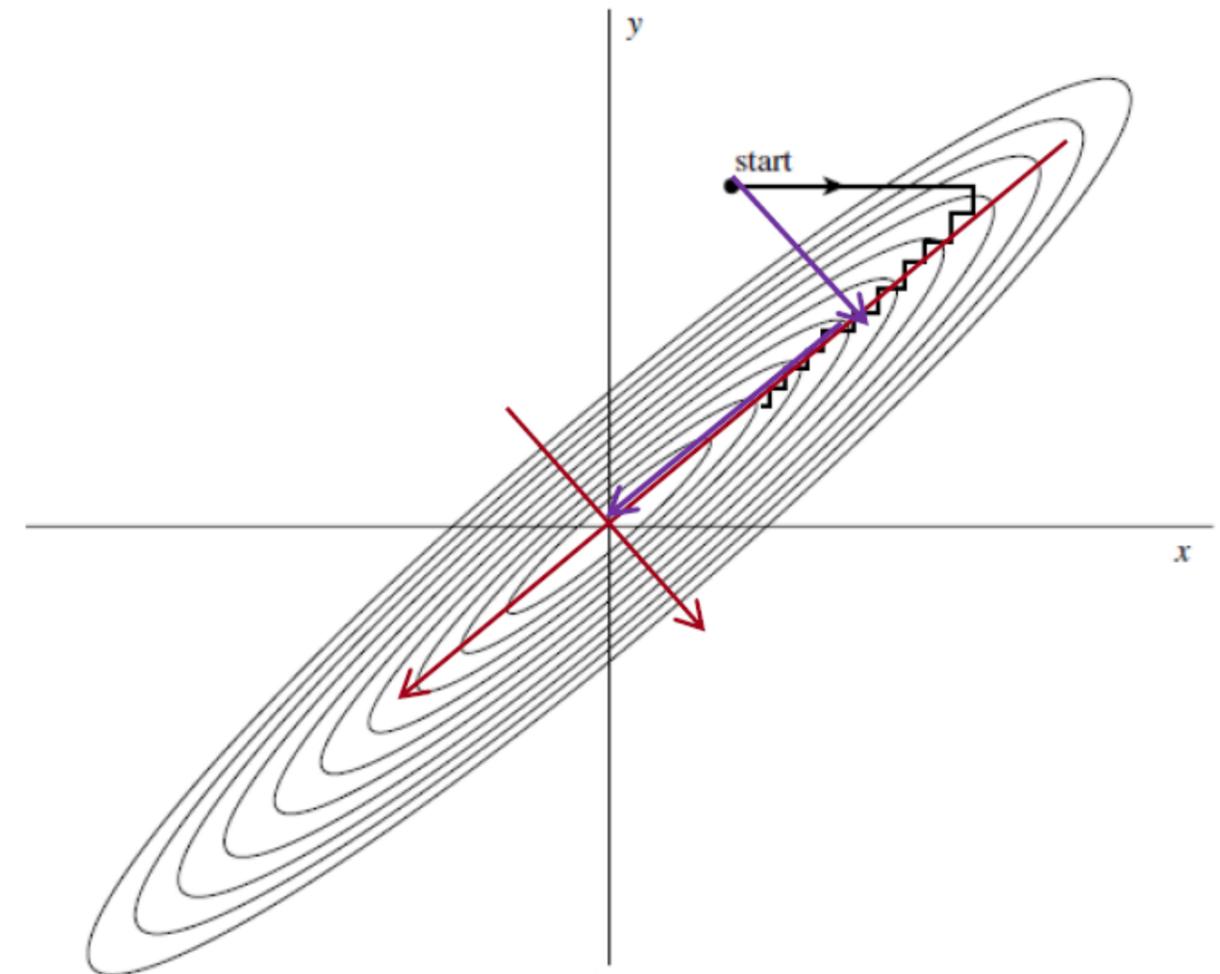


Large tournament size has chosen to reach fast convergence.



~ 90 minutes

- Proposed by Michael J. D. Powell in 1964 [2]
- The function need not be differentiable, and **no derivatives** are taken.
- Pattern or Direction Search Methods
- Powell's method can update the directions using past search results to develop a conjugate set.
- Only conjugate direction sets are be used to avoid infinite rotation in a circle.

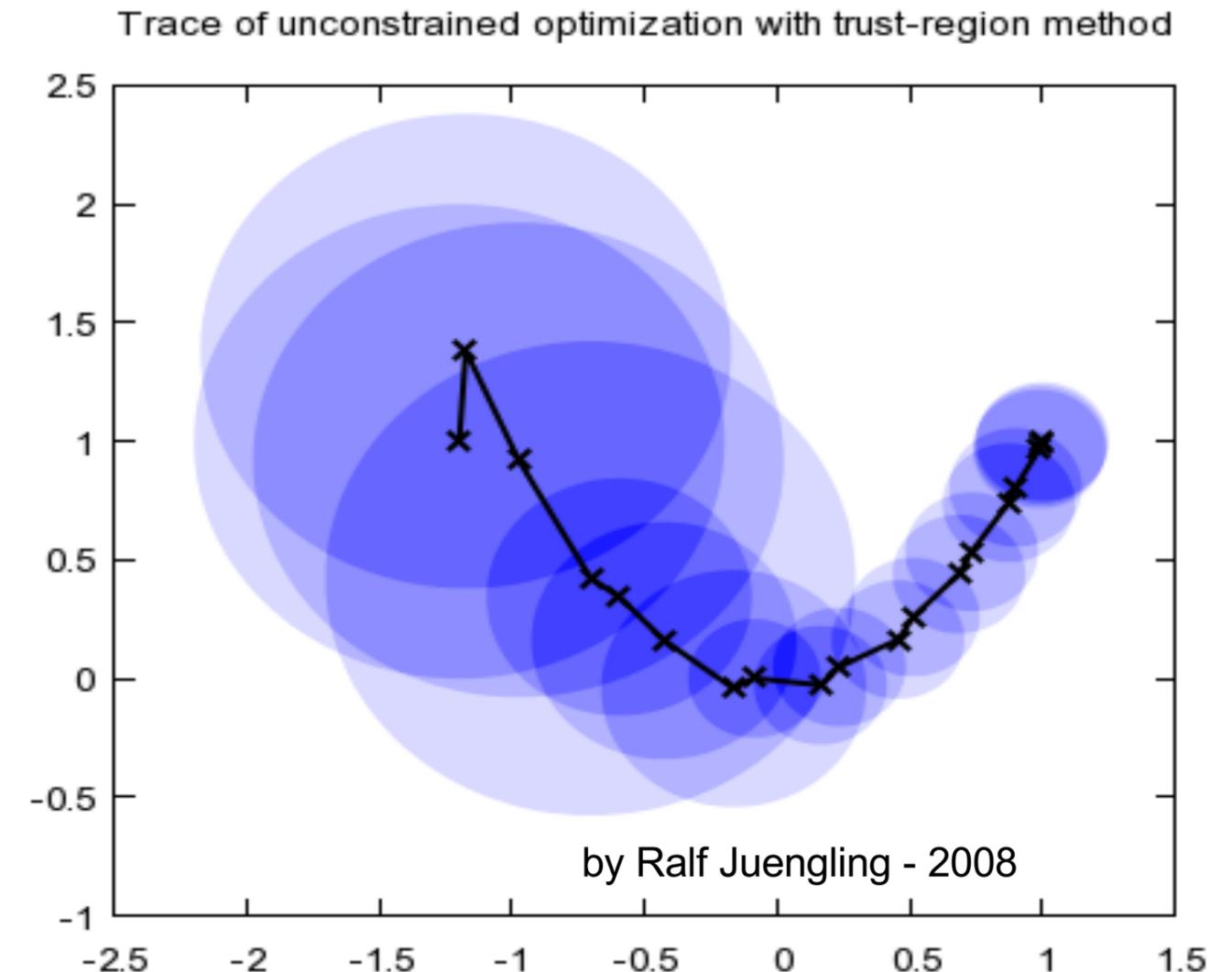


- 1D optimizer with multi variables

[2] M.J.D. Powell. Comput. J., 7, 155–162, 1964. doi: 10.1093/comjnl/7.2.155

# Bound Optimization BY Quadratic Approximation (BOBYQA)

- BOBYQA is a deterministic method and no derivatives are taken during the optimization.
- Proposed by Michael J. D. Powell in 2009.
- BOBYQA is sequential trust–region algorithm that employs **quadratic approximations** to the objective function [2]
- The quadratic models are updated regularly to include new information about the objective function, such as the difference between two gradient vectors.



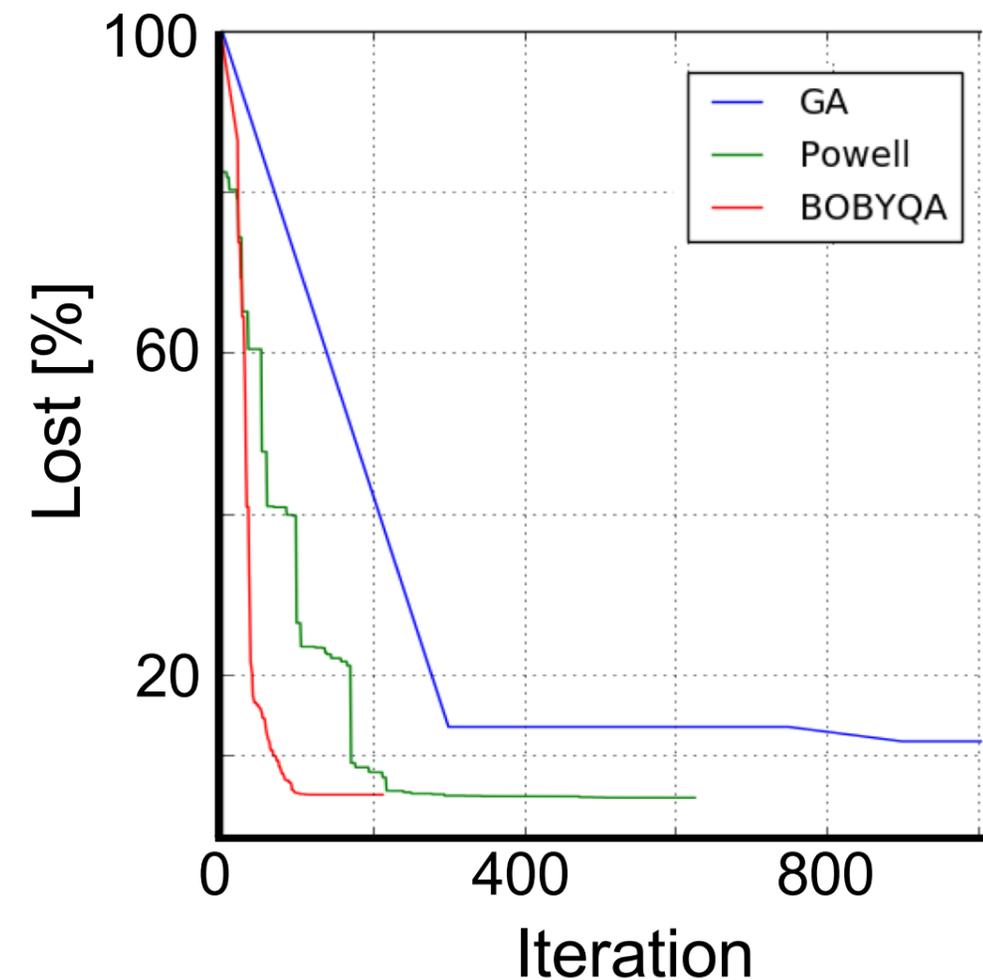
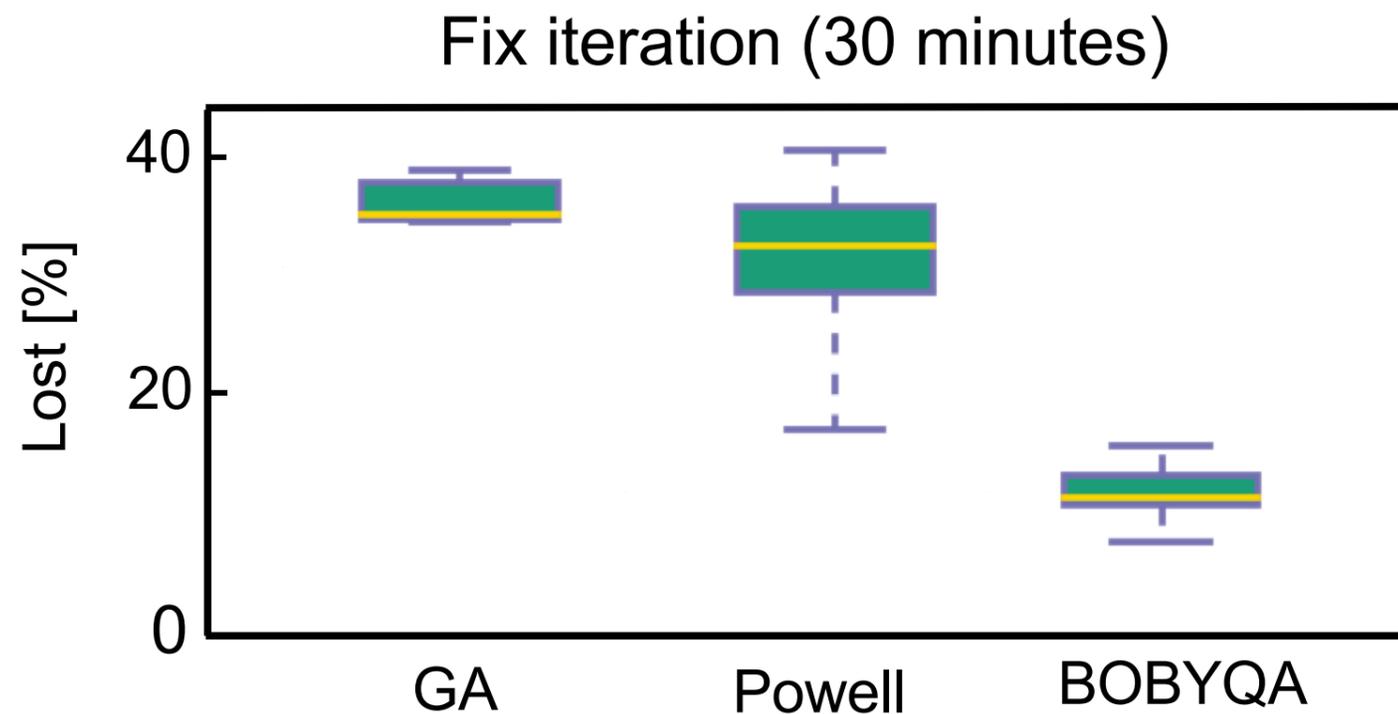
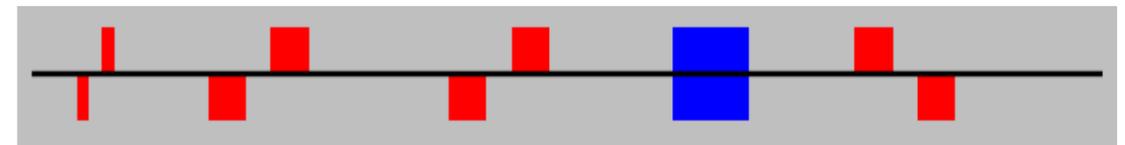
- In Py-BOBYQA robustness against noise is implemented. [3]

[2] M. J. D Powell, technical report DAMTP 2009/NA06, Cambridge (2009),  
[3] C. Cartis, arXiv:1804.00154, (2018), <https://pypi.org/project/Py-BOBYQA>

Proposed to with Verena + Simon, 2019

- Comparison between GA, Powell, BOBYQA for beam line optimization
- Optimization aim is to minimize beam loss
- **BOBYQA** is the fastest of the examined algorithms

Part of CRYRING@ESR Local Injector



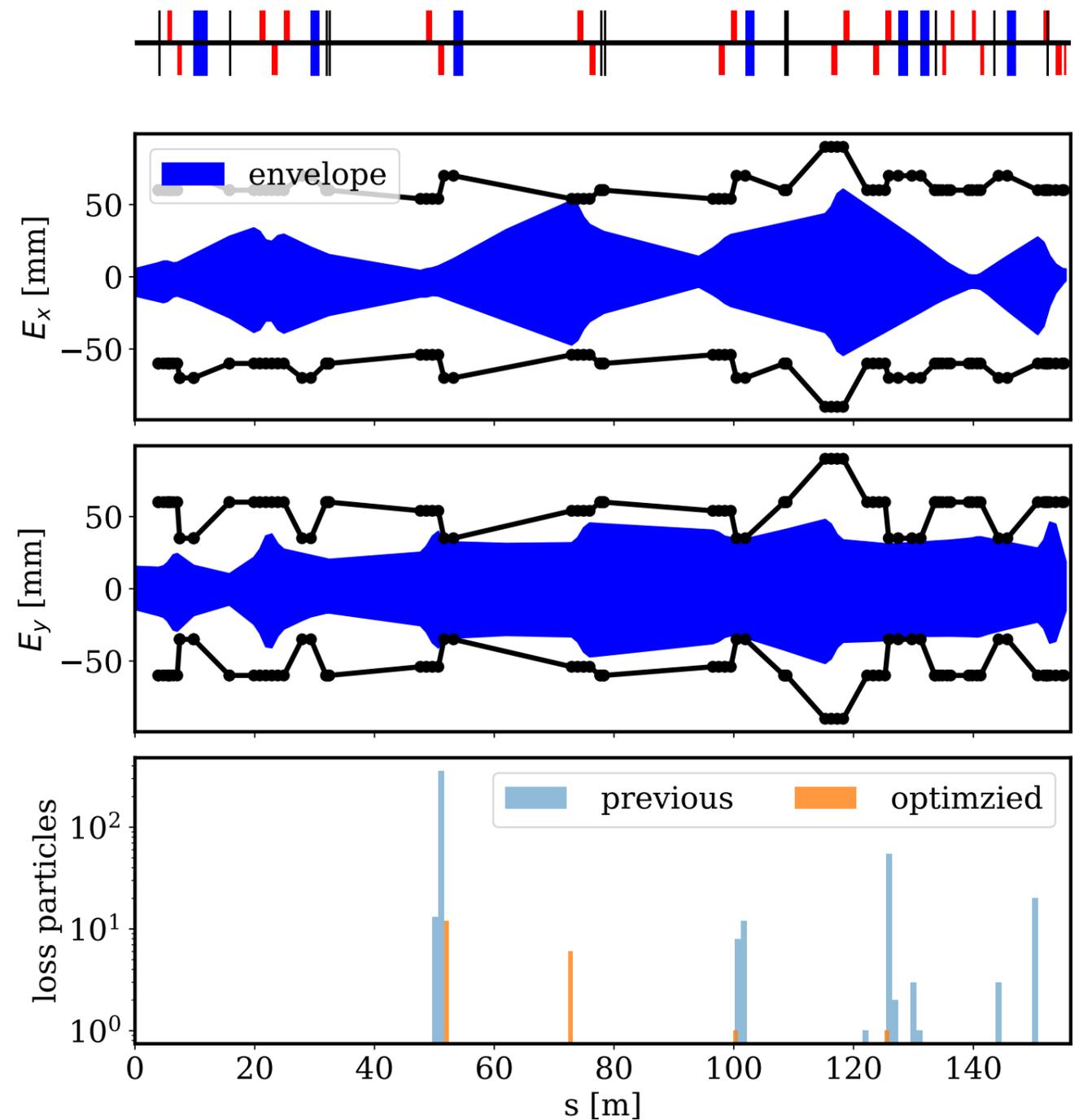
[14] Bachelor-Thesis von Maike Wolf (2019)

- Optimization aim is to minimize beam loss and reach simultaneous a small focused beam at the experiment target.
- Weighting factor approach is used for multi-objective reduction and the composite objective function is than optimized.  
  

$$\text{loss, betaX, betaY} = \text{sis18 hades(..)}$$

$$\text{comp\_func} = w1*\text{loss} + w2*\text{betaX} + w3*\text{betaY}$$
- Online algorithm needs to be aware of the noise like Py-BOBYQA<sup>[3]</sup> or RCDS<sup>[15]</sup>.

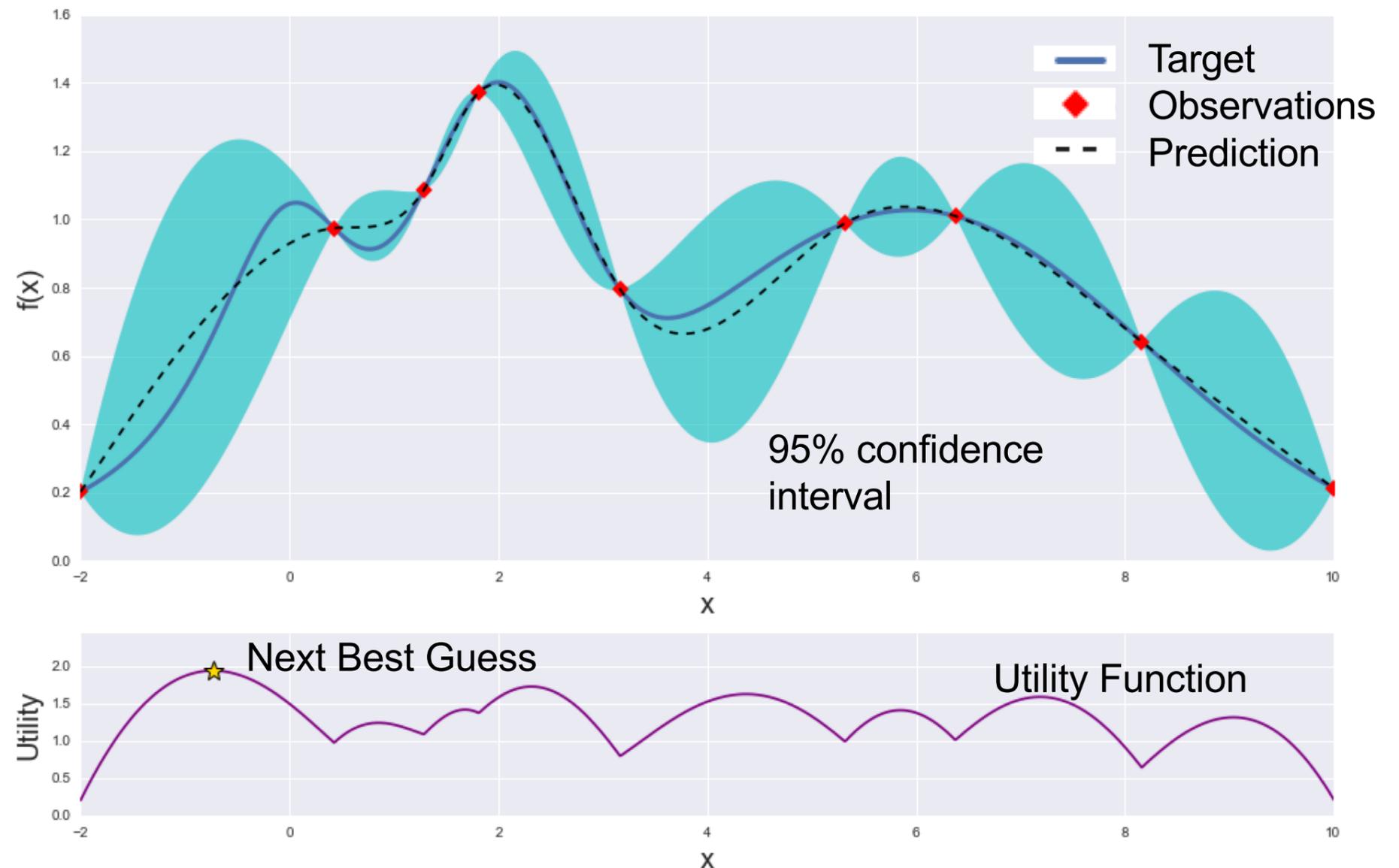
HADES beam line



[15] X. Huang, Nucl. Instrum Methods A, 726, 77-83 (2013)

Gaussian Process and Utility Function After 9 Steps [5]

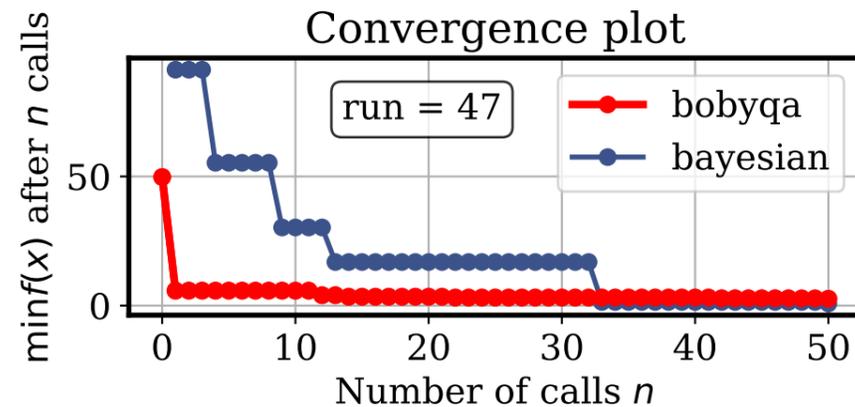
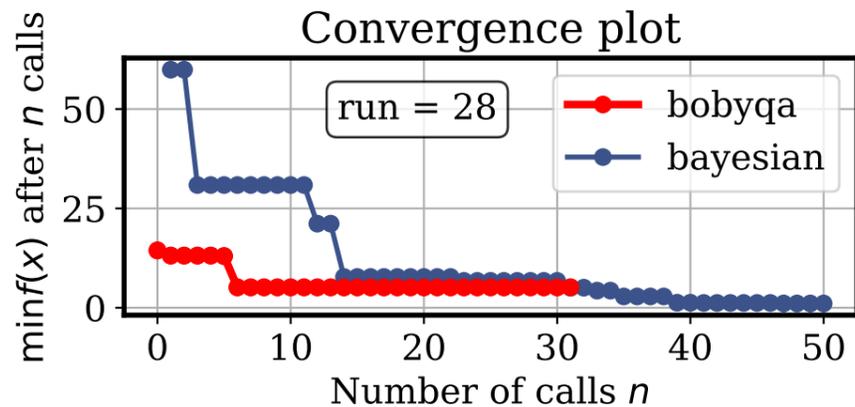
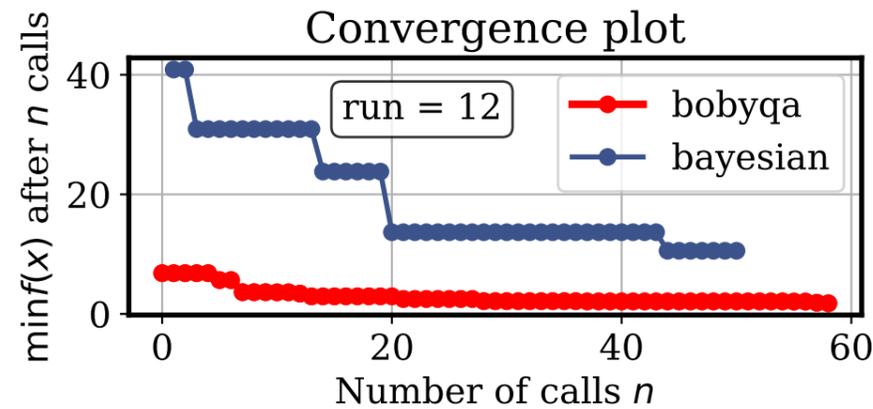
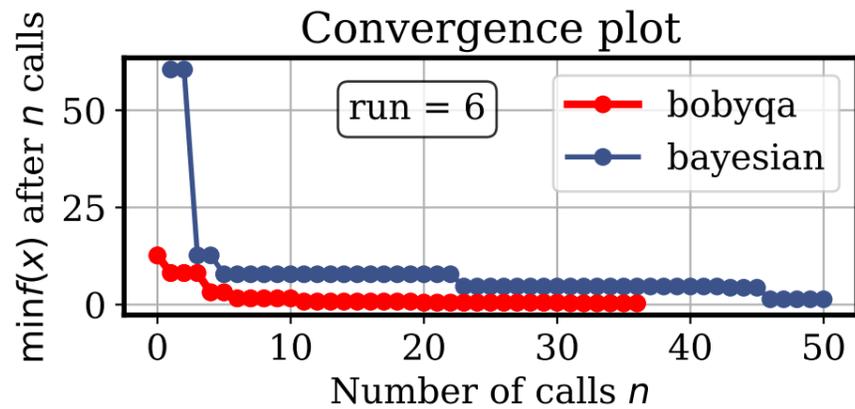
- Probabilistic model of optimization function is construed and then exploits this model to make decisions where to evaluate the function next.
- Gaussian process prior will express assumption about the optimization function.
- Chosen utility function defined from this **surrogate model** where to evaluate the function next.
- Multi-objective Bayesian optimization algorithm (recently available) [6]



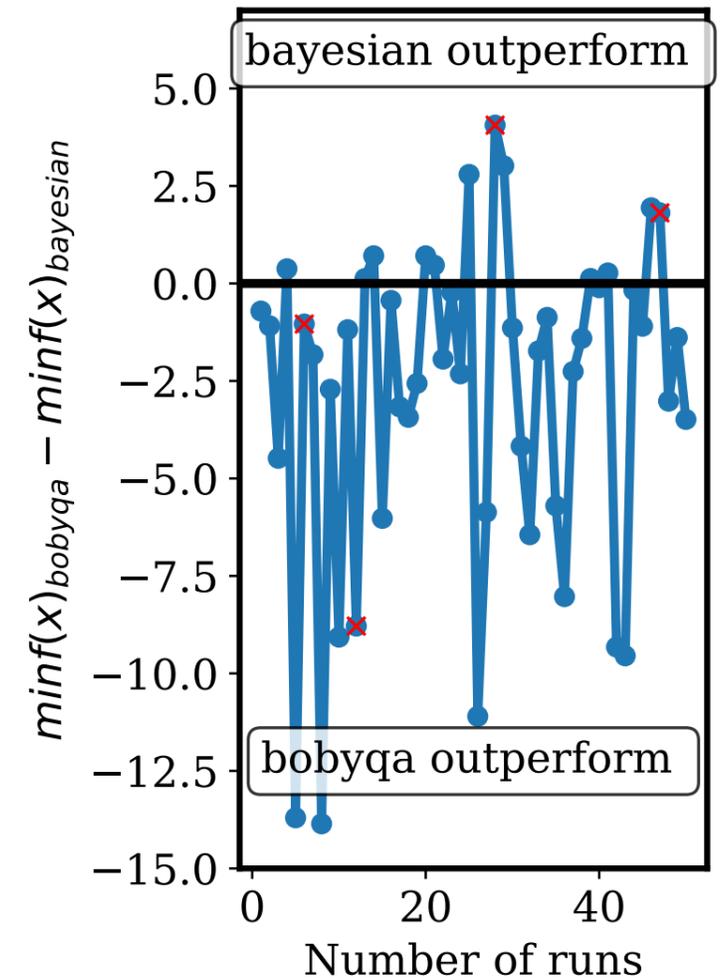
[5] F. Noqueira, <https://github.com/fmfn/BayesianOptimization>

[6] <https://github.com/ppgaluzio/MOBOpt/wiki>

# Optimization of beam lines



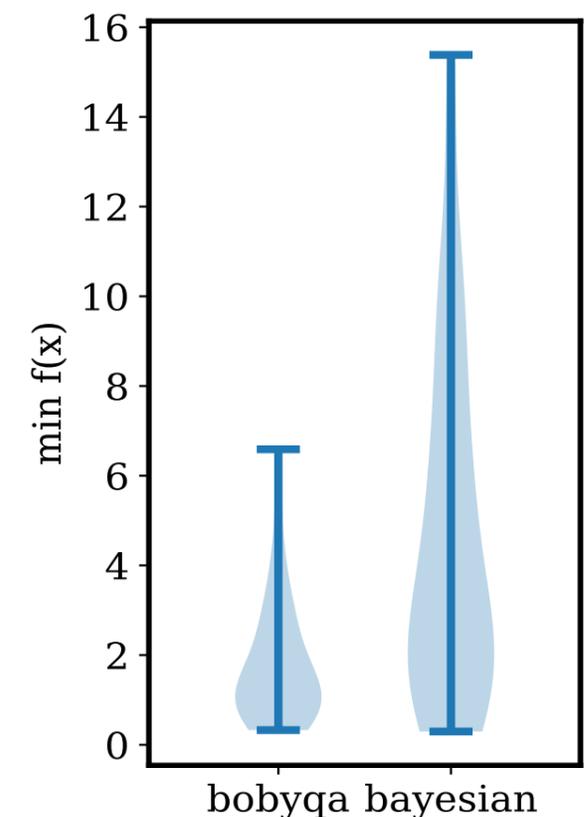
[17]



- The Bayesian Optimization<sup>[4]</sup> is often outperform by Py-BOBYQA<sup>[3]</sup>, **as good initial values are available.**
- As next step, **external boundary conditions** has to be taken into account. Such an optimization problem prefer must likely the adaptive and safe Bayesian optimization<sup>[16]</sup>.

[16] J. Kirschner et al., arXiv 1902.03229 (2019)

[17] S. Appel et al., J. Phys. Conf. Ser 1350 (2019) 012104



- MIT optimization in **Java** for optimization at CRYRING\* \* by W. Geithner
- The Accelerator Construction Set in **C++** for TK optimization\*\* \*\* by S. Reinmann
- The tools are highly specific to a certain context and task resulting in a hard coding of an algorithm or of machine
- **Missing**: A more global tool with a large validated optimization algorithms and machine learning data bank
  - An agnostic machine learning optimizer toolkit is **already** developed for the CERN accelerators
  - **Create** a virtual accessible beam diagnostic data and optimizer toolkit for GSI and other EU-Labs (open source) based on CERN python toolkit
  - Find **usable optimization and ML algorithms** for accelerator problems.

# Soon hiring a scientific staff member for three years, E13



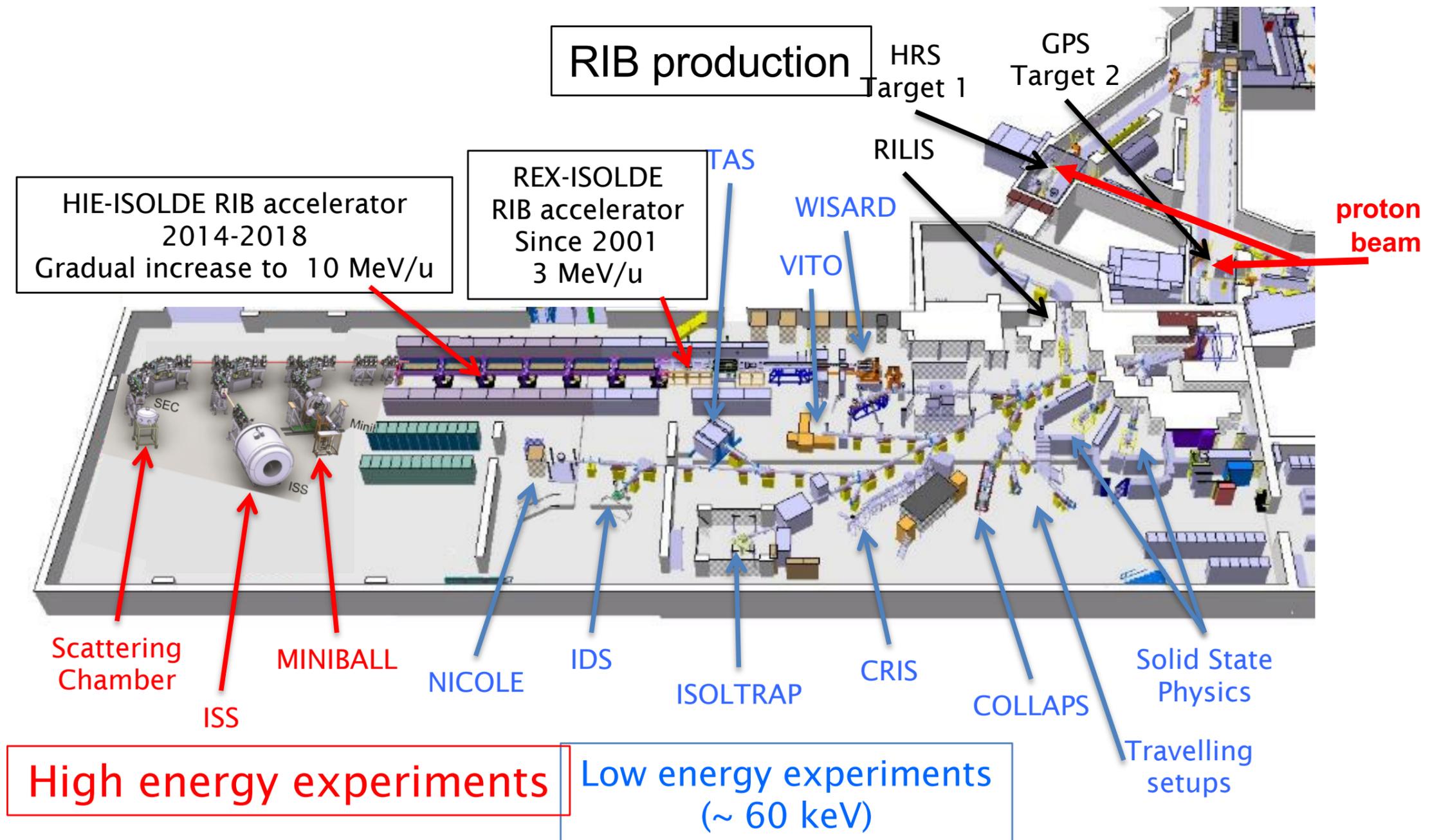
## Your duties:

- Advancement and implementation of ML algorithms for machine optimization tasks
- Scientific secretary for the EUROLABS WP5 Task 3
- Cooperation with the Controls + Accelerator Systems Departments at GSI + CERN
- Preparation, execution and documentation of validation campaigns at GSI + CERN

## Your profile:

- M.Sc. in physics (or a comparable discipline) and PhD, preferred in accelerator physics
- experience with software tools and programming languages (preferably Java + python)
- experience with machine learning and optimization algorithms
- broad knowledge of accelerator control systems and accelerator physics is desired

# Experiments at ISOLDE



# CPS Optimizer at ISOLDE, Example 1:



Monday, November 26th 2018 14:18:20 written by isoop@CWO-508-ISO2 3165983 (LGBK\_EDITOR)

We had to do some beam tuning to CRIS after the changes. Currently using the **optimizer** on FC3 which gave a factor of 4 improvement. Running it one more time.

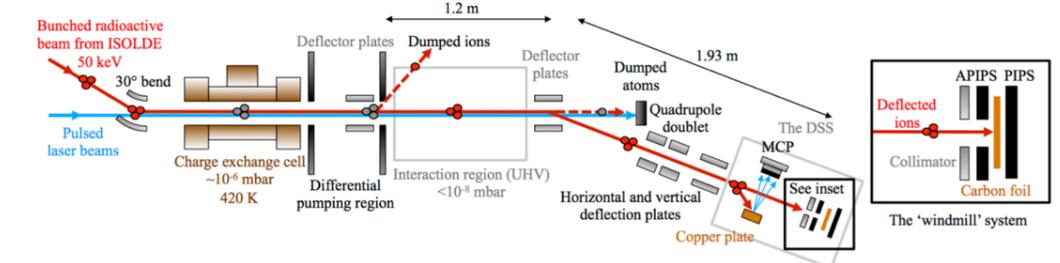
Screenshot of the setting used now attached.

/CRIS FrW

The screenshot shows the CPS Optimizer v2.4.1 interface. It features a control panel on the left with parameters for various quadrupoles (YCB0.QS30-V(VER), YCB0.QS40-V(FOC), YCB0.QS40-V(HOR), YCB0.QS40-V(VER), YCB0.QP50-V) and detectors (YCD0.BFC5100). The central area contains two graphs: the top one shows Current (AQN) vs Time, and the bottom one shows YCD0.BFC5100(A) vs Time. The bottom right has 'START' and 'STOP' buttons.

[2]

THE CRIS TECHNIQUE



[1]

Users are responsible for tuning beam into their machine

Frequently using the CPS optimizer [3] for ISOLDE electrostatic elements

[1] <https://isolde-cris.web.cern.ch/>

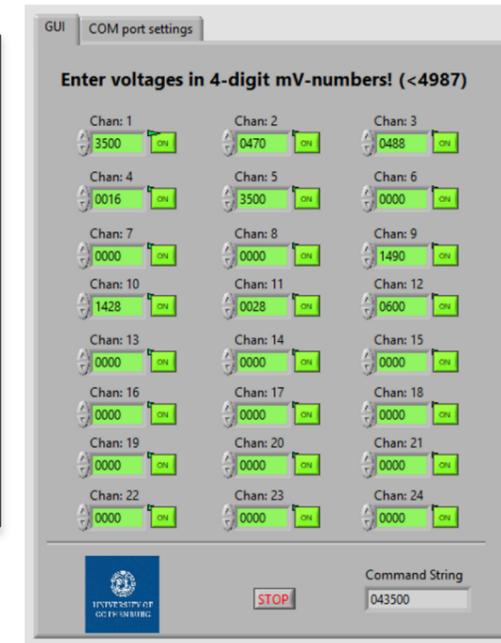
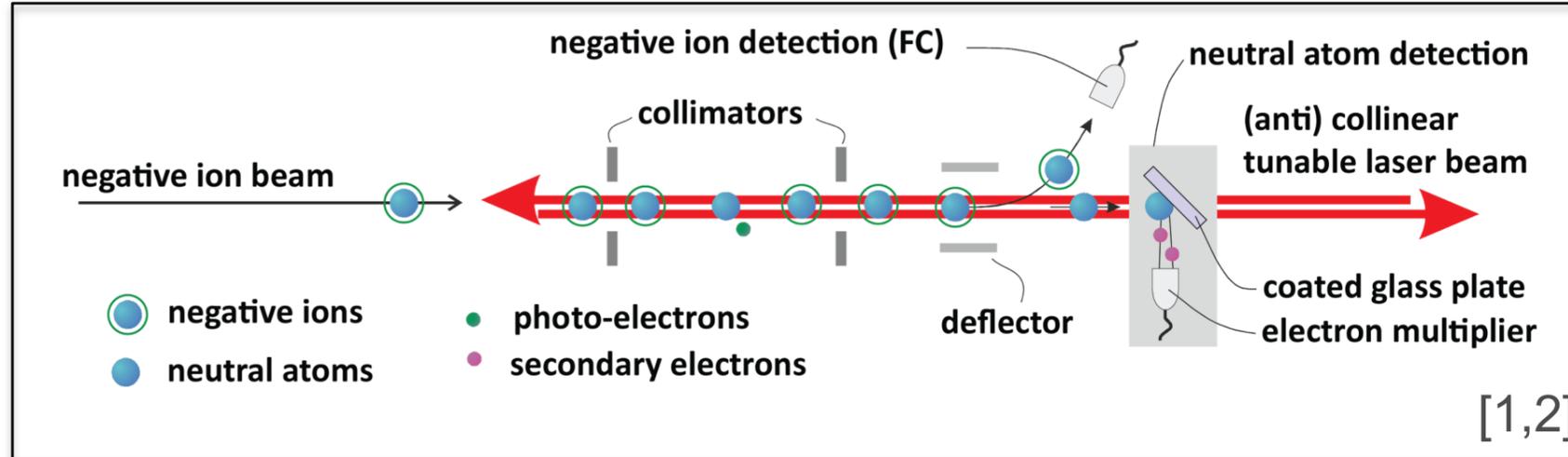
[2] <https://be-op-logbook.web.cern.ch/elogbook-server/GET/showEventInLogbook/3165983>

[3] Piselli, E., & Akroh, A. (2017). New CERN Proton Synchrotron Beam Optimization Tool. <https://doi.org/10.18429/JACoW-ICALEPCS2017-TUPHA120>

# CPS Optimizer at ISOLDE, Example 2:

# GANDALPH

Gothenburg ANion Detector for Affinity measurements by Laser PHotodetachment



## CERN ACCELERATORS BEAM OPTIMIZATION ALGORITHM

E. Piselli<sup>1</sup>, A. Akroh<sup>1</sup>, K. Blaum<sup>2</sup>, M. Door<sup>2</sup>, D. Leimbach<sup>1,3</sup>, S. Rothe<sup>1</sup>

<sup>1</sup>CERN, Geneva, Switzerland

<sup>2</sup>Max Planck Institute for Nuclear Physics, Heidelberg, Germany

<sup>3</sup>Johannes Gutenberg University Mainz (IKP) Institute for Nuclear Physics, Mainz, Germany

“We have now successfully demonstrated the simultaneous optimization of ISOLDE parameters and experiment parameters using a user-generated signal (event rate from an electron multiplier). For this, we have written an interface that enabled us to set parameters of the user’s electrostatic elements via a LabVIEW Common Middle Ware (CMW) wrapper [7]. We have created a virtual device in the CERN Controls Database, that contained eight control parameters and one device that represented the signal.”

[3]

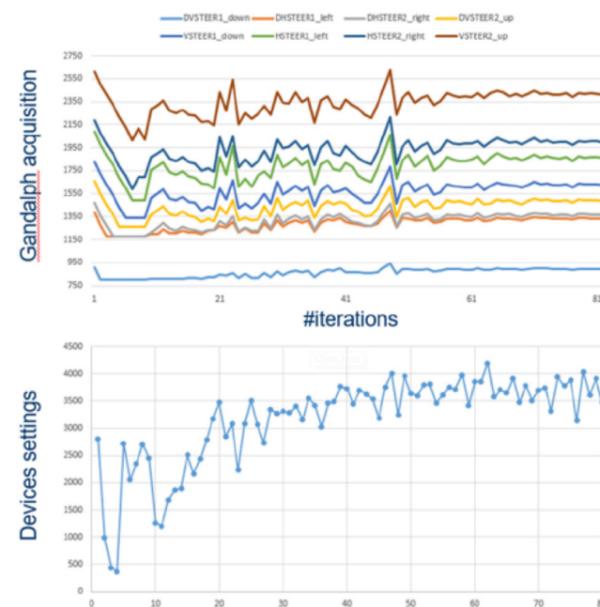


Figure 10: Gandolph optimization, for details see text.

[1] S.Rothe *et al.* *J. Phys. G: Nucl. Part. Phys.* **44** 104003 (2017)  
<https://doi.org/10.1088/1361-6471/aa80aa>

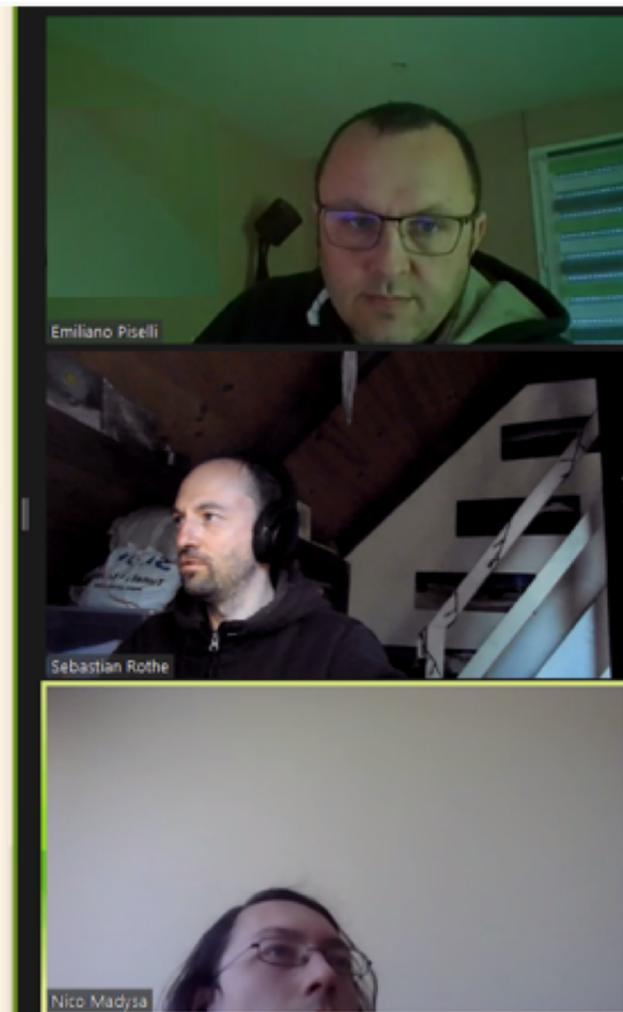
[2] D. Leimbach *et al.* *Nat Commun* **11**, 3824 (2020).  
<https://doi.org/10.1038/s41467-020-17599-2>

[3] E. Piselli *et al.* CERN Accelerators Beam Optimization Algorithm. *JACOW*, 1379 (2020)  
<https://doi.org/10.18429/JACoW-ICALEPCS2019-WEPHA124>

# Optimizer implementation for ISOLDE GPS



The screenshot shows the GeOFF v0.1.0 interface. On the left, a list of machines is displayed under 'Machine: SPS'. The central panel shows an 'Objective function' graph with 'Cost (norm.u.)' on the y-axis (0 to 1) and 'Step' on the x-axis (0 to 1). The right panel shows a log console with terminal output, including the command `python -m acc_app_optimisation --lsa-server=next cern_isolde_prototype_env/ --no-capture-stdout` and various system messages.



Emiliano

/srr

Nico

# Optimizer implementation for ISOLDE GPS



```
ment already satisfied: numpy==1.17 in /nfs/cs-ccr-nfsop/nfs1/vol30/local/share/python/acc-py/base/2020.11/lib/python3.7/site-packages (from acc-app-optimisation==0.1.4) (1.19.2)
ment already satisfied: torch==1.4.0 in /opt/venvs/isolde/lib/python3.7/site-packages (from stable-baselines3==0.11.1->acc-app-optimisation==0.1.4) (1.8.1)
ment already satisfied: matplotlib==3.0 in /opt/venvs/isolde/lib/python3.7/site-packages (from cern-awake-env==0.15.0->acc-app-optimisation==0.1.4) (3.4.1)
```

GeOFF v0.1.4 (LSA NEXT) (auf cwe-513-vpl073.cern.ch)

View Info

Machine: ISOLDE

TGM User LSA Context

Num. Optimiz... Train RL A... Run RL A...

Environment

IsoldeEnv-v0

Configure

Show constraints

Algorithm

Nelder-Mead

Configure

Start Stop Reset

Actors

Objective and Constraints

Objective function

Actor values (norm. u.)

Cost (norm. u.)

Step

RL Training

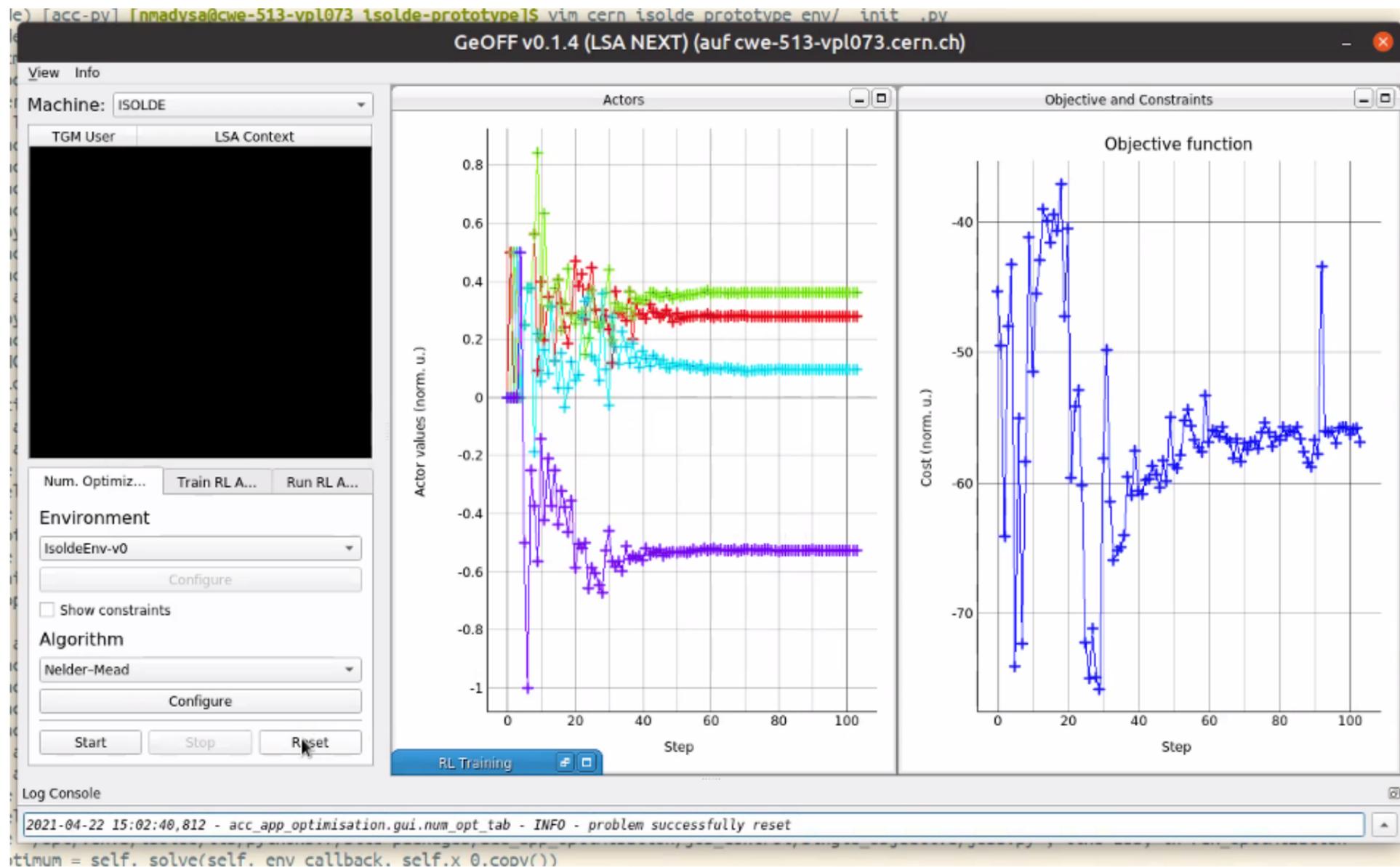
Log Console

```
2021-04-22 14:48:05,222 - acc_app_optimisation.gui.num_opt_tab - ERROR - Traceback (most recent call last):
File "/opt/venvs/isolde/lib/python3.7/site-packages/acc_app_optimisation/gui/num_opt_tab.py", line 123, in get_or_load_problem
return self.opt_builder.make_problem()
File "/opt/venvs/isolde/lib/python3.7/site-packages/acc_app_optimisation/job_control/single_objective/builder.py", line 57, in make_problem
token=self.token_source.token,
File "/opt/venvs/isolde/lib/python3.7/site-packages/acc_app_optimisation/envs/_init_.py", line 87, in make_env_by_name
kwargs["japc"] = make_japc()
File "/opt/venvs/isolde/lib/python3.7/site-packages/acc_app_optimisation/job_control/single_objective/builder.py", line 68, in get_japc_or_raise
raise CannotBuildJob("no LSA context selected")
acc_app_optimisation.job_control.base.CannotBuildJob: no LSA context selected

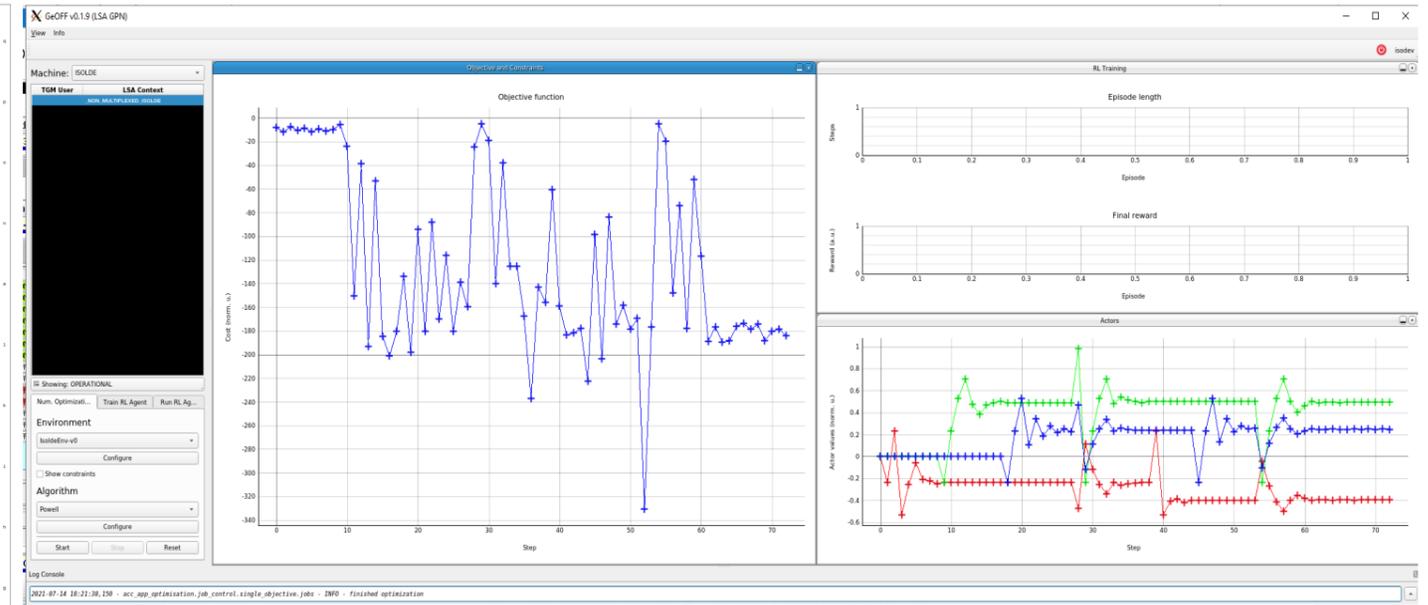
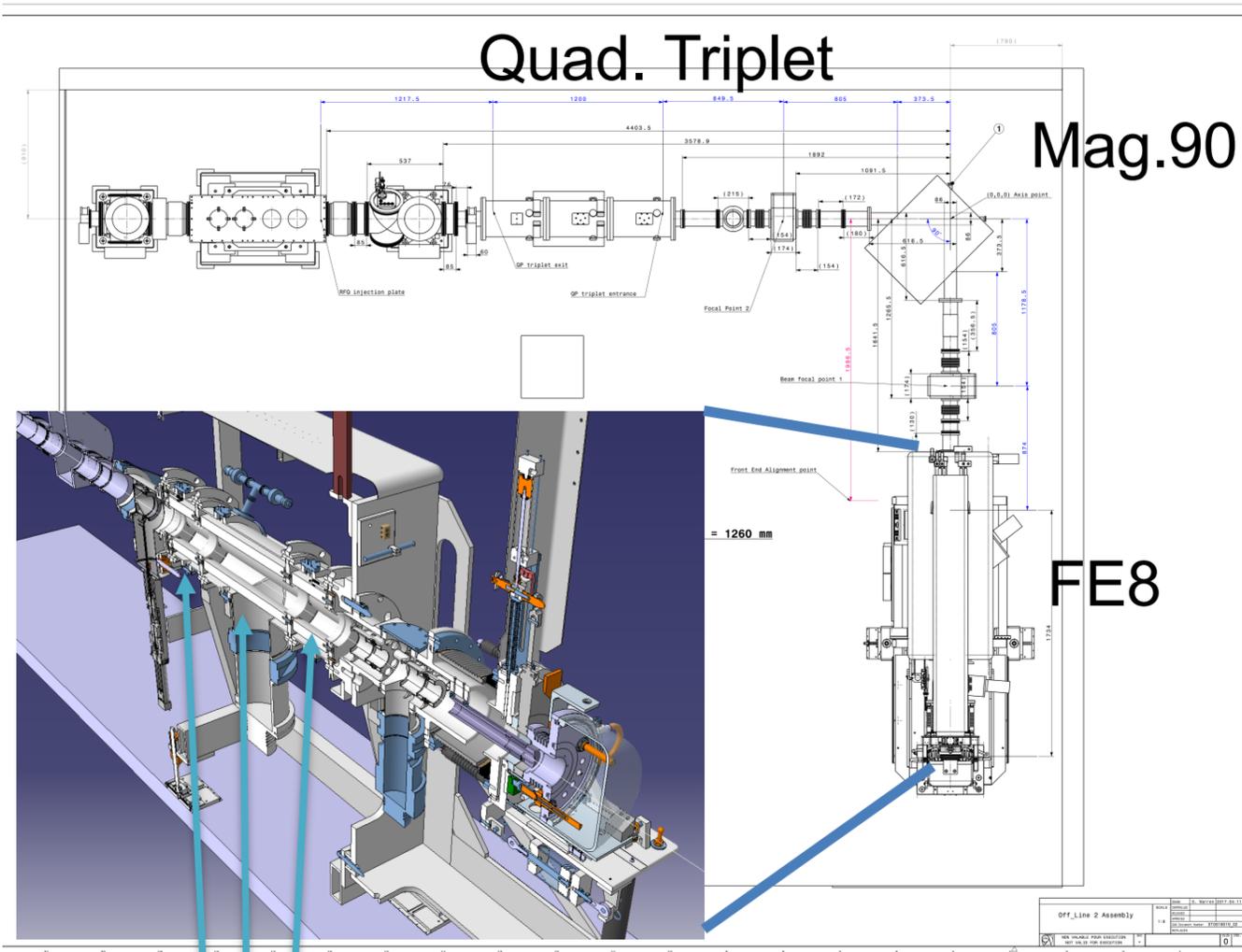
2021-04-22 14:48:05,224 - acc_app_optimisation.gui.num_opt_tab - ERROR - Aborted initialization due to the above exception

2021-04-22 14:48:05,224 - acc_app_optimisation.gui.num_opt_tab - ERROR - Aborted initialization due to the above exception
File "/opt/venvs/isolde/lib/python3.7/site-packages/acc_app_optimisation/job_control/single_objective/builder.py", line 57, in make_problem
token=self.token_source.token,
File "/opt/venvs/isolde/lib/python3.7/site-packages/acc_app_optimisation/envs/_init_.py", line 87, in make_env_by_name
kwargs["japc"] = make_japc()
File "/opt/venvs/isolde/lib/python3.7/site-packages/acc_app_optimisation/job_control/single_objective/builder.py", line 68, in get_japc_or_raise
```

# Optimizer implementation for ISOLDE GPS



# Optimizer mod. for ISOLDE Offline 2

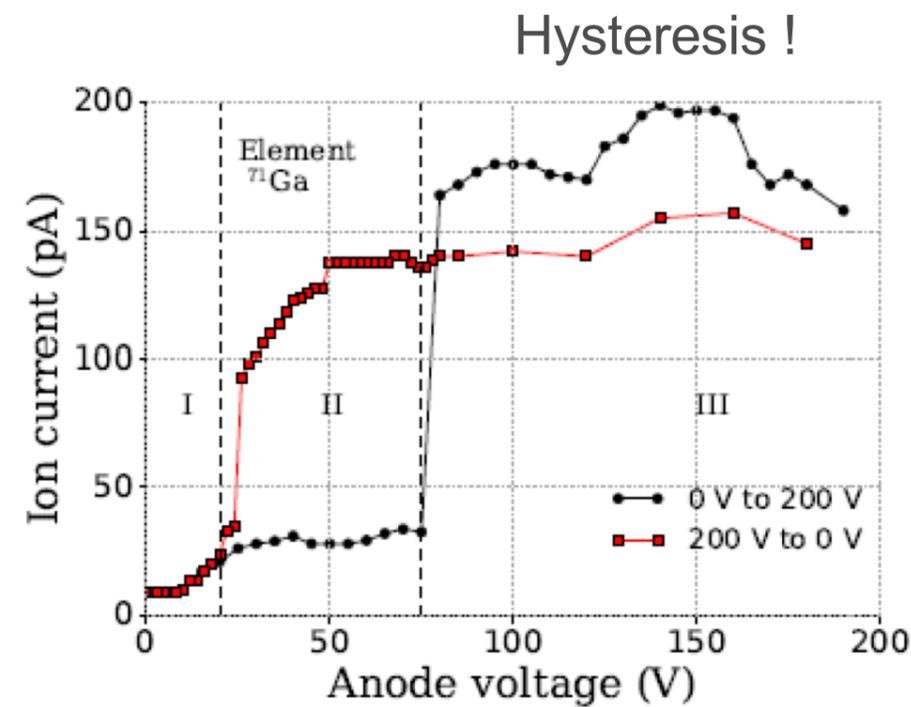
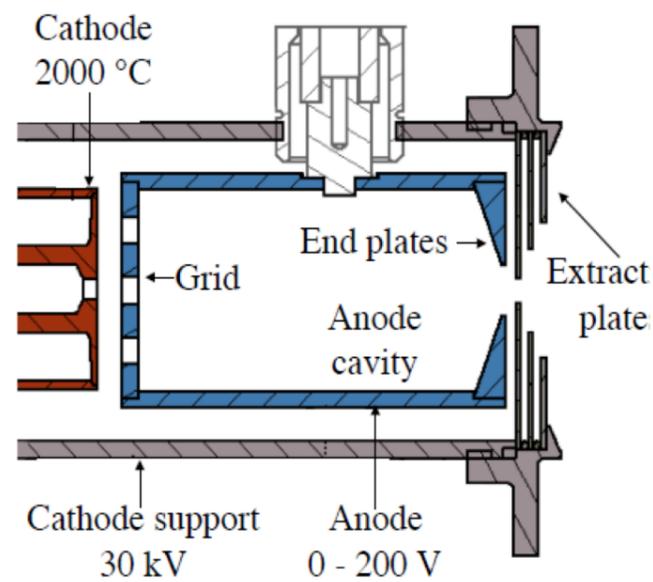


N. Madysa *et al.*

<https://gitlab.cern.ch/be-op-ml-optimization/envs/isolde-example-optimization>

YOL2_QP30	ON	ON	REMOTE	2000.00	1998.63	2001.664
YOL2_QP40	ON	ON	REMOTE	1033.00	1034.50	1040.582
YOL2_QP50	ON	ON	REMOTE	2000.00	1998.63	1996.094
YOL2_QP100	OFF	OFF	REMOTE	000.00	10.10	5.570

# Ion Sources: FEBIAD



(a)

## Parameters

- Anode voltage
- Electron current
- Magnetic field
- Einzel lens voltage

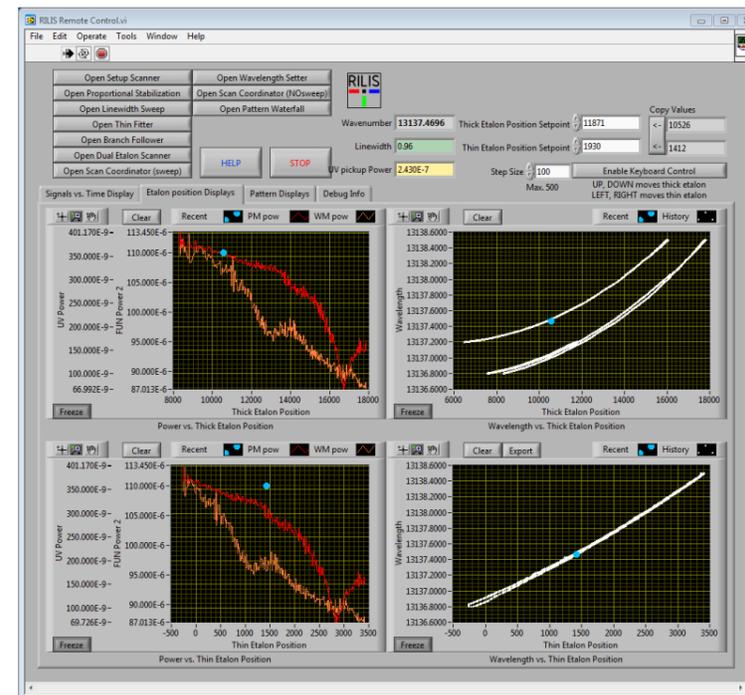
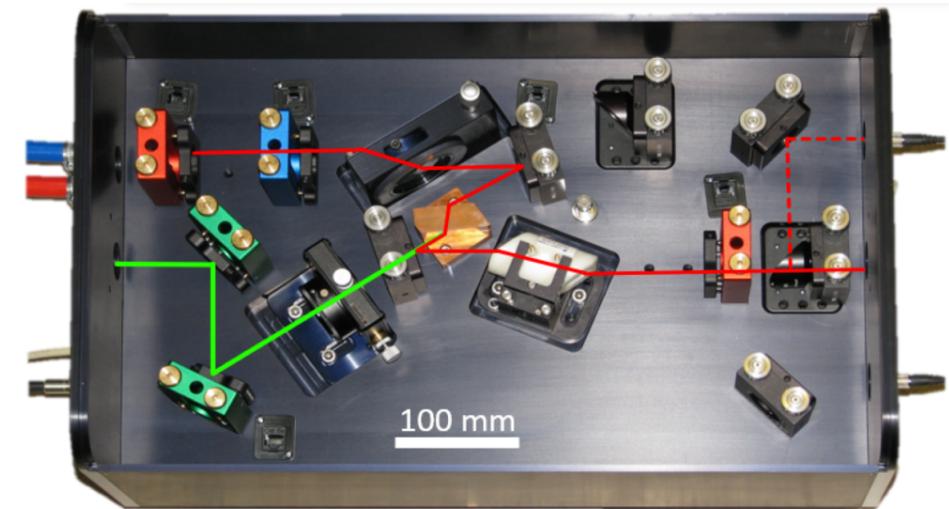
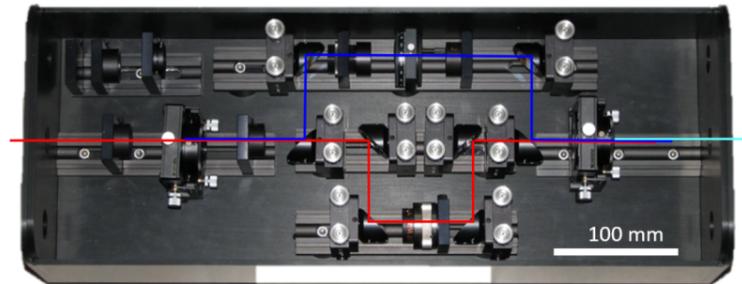
## Observables:

- Intensity
- beam shape
- transverse emittance

Y. Martinez Palenzuela, Thesis (<https://lirias.kuleuven.be/handle/123456789/636675>)

# Ion sources: RILIS

Valentin Fedosseev *et al* 2017 *J. Phys. G: Nucl. Part. Phys.* **44** 084006  
 Doi: [10.1088/1361-6471/aa78e0](https://doi.org/10.1088/1361-6471/aa78e0)



- Laser cavity has >5 parameters
- Optomechanics has hysteresis !

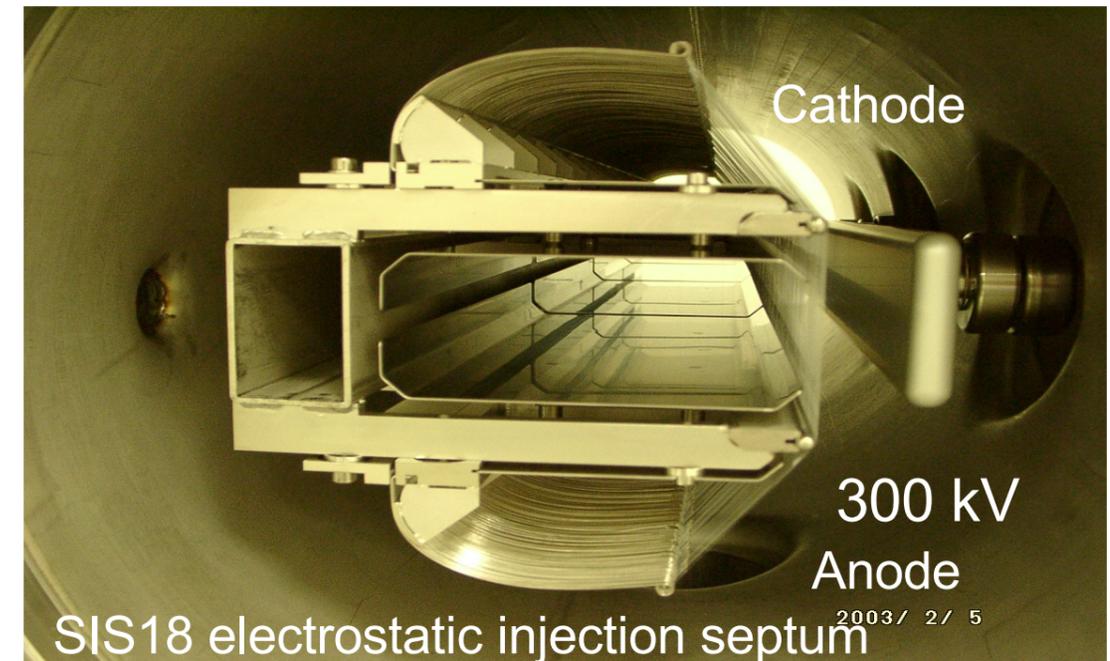
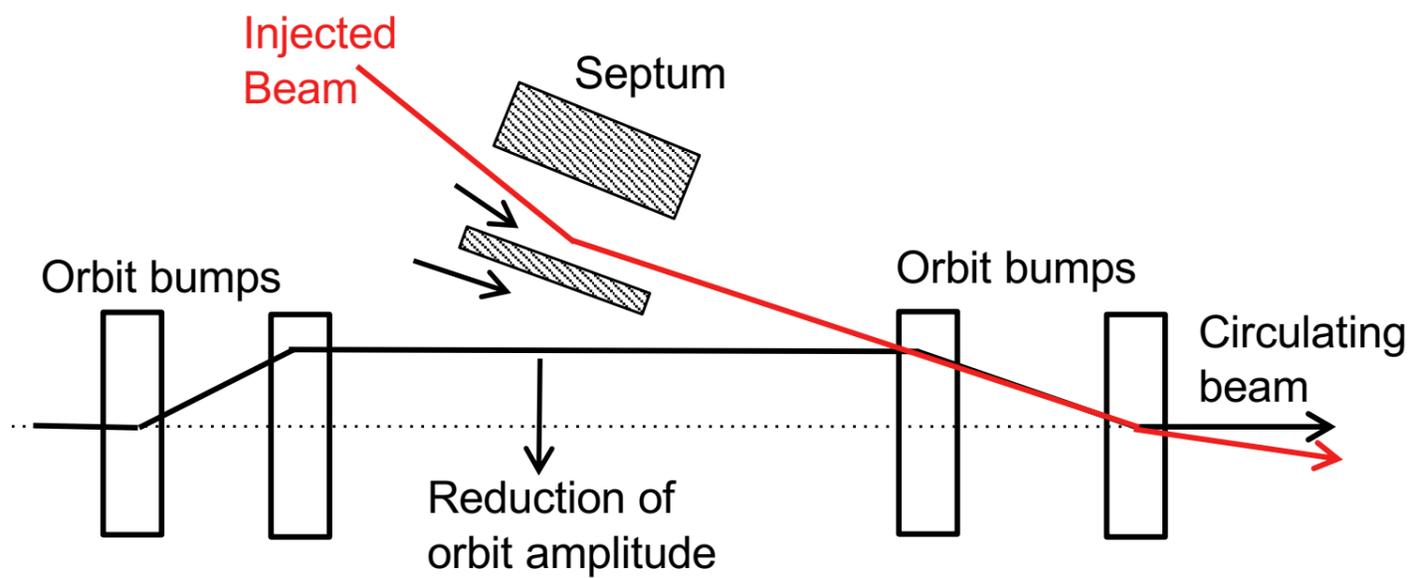
## Observables:

- Power
- Linewidth
- Pulse delay
- Beam shape

**Thank you for your attention**

# Model: Multi-turn injection

MTI has to respect Liouville's theorem:  
 Injected beams only in free space



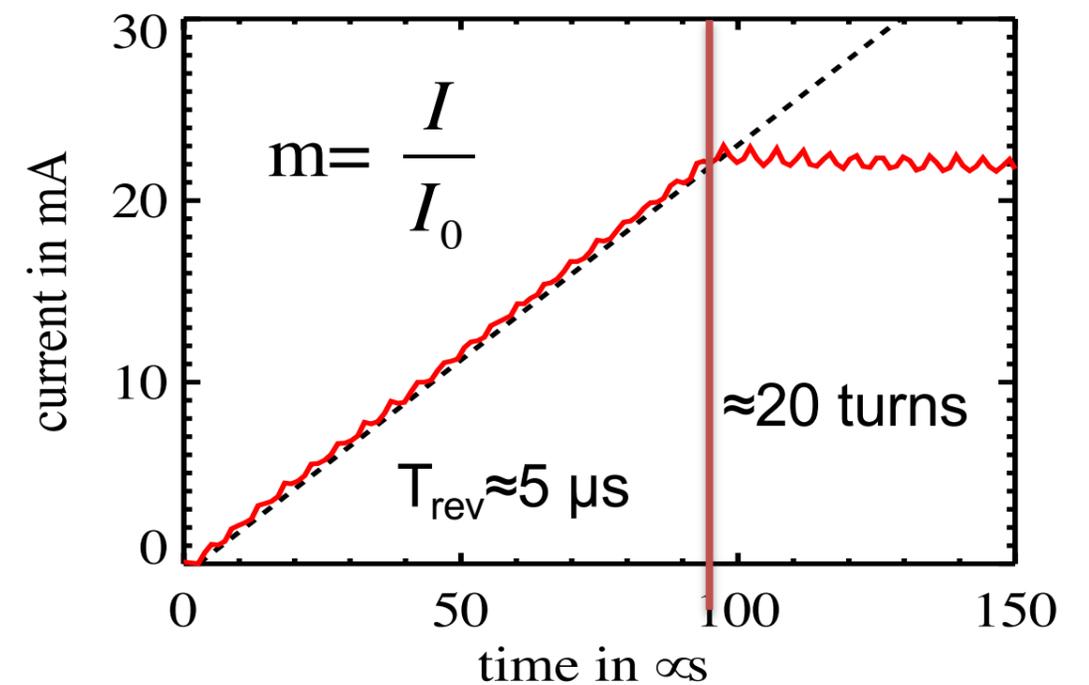
Gain factor should be high as possible

Injection loss should be low as possible

$$m = \frac{I}{I_0}$$

$$\eta = \frac{I_{loss}}{nI_0}$$

Measured MTI performance in SIS18



# MTI into SIS18: Model

## Multi-objectives:

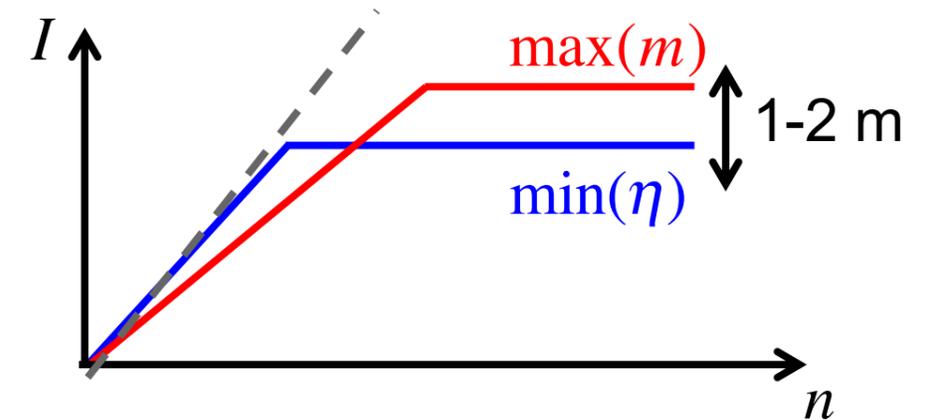
- Gain factor (maximize)  $I = mI_0$
- Beam loss (minimize)  $\eta = \frac{I_{loss}}{nI_0}$
- Emittance  $\epsilon_x$

## Constraints:

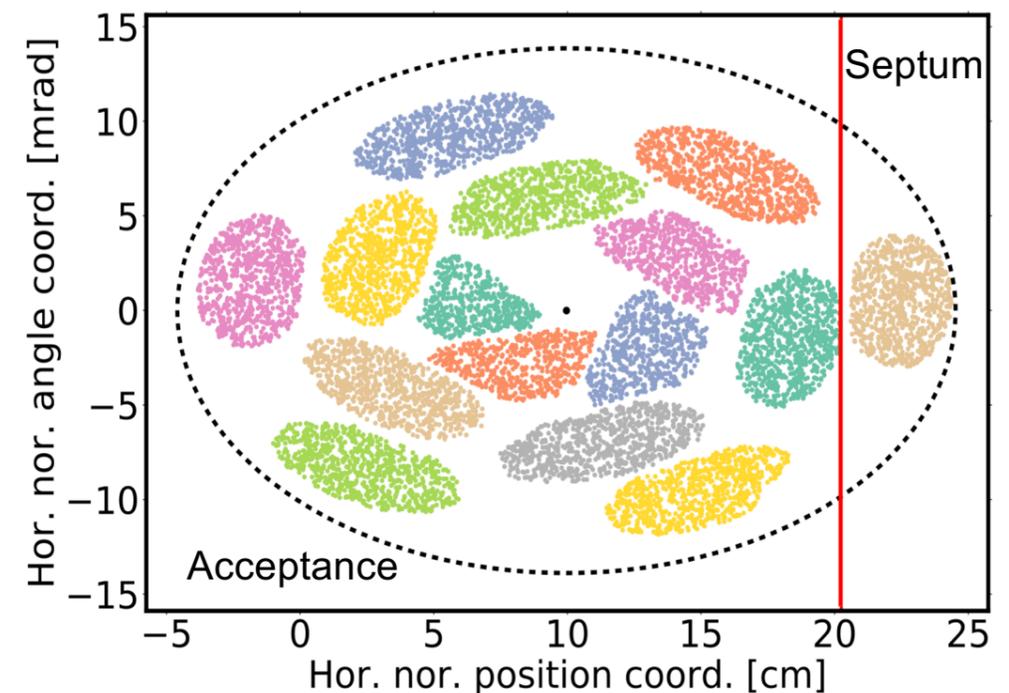
- Position of septum, machine acceptance

## Parameters:

- Position of incoming beam at septum
- Initial bump amplitude and its decreasing
- Injected turns
- Horizontal tune and emittance

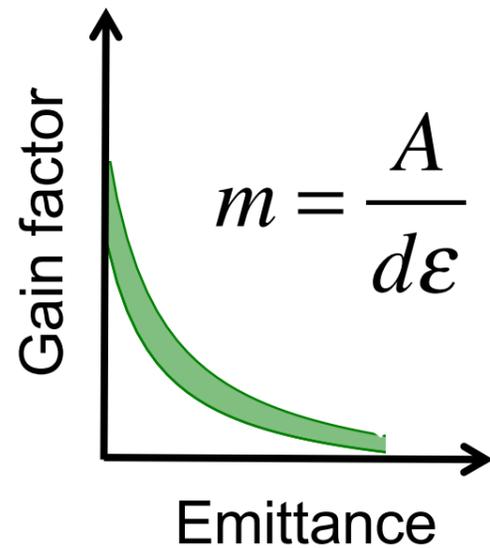


Model in simulation code



# Injector brilliance depending

## EMittance Transfer EXperiment (EMTEX)<sup>[6]</sup>

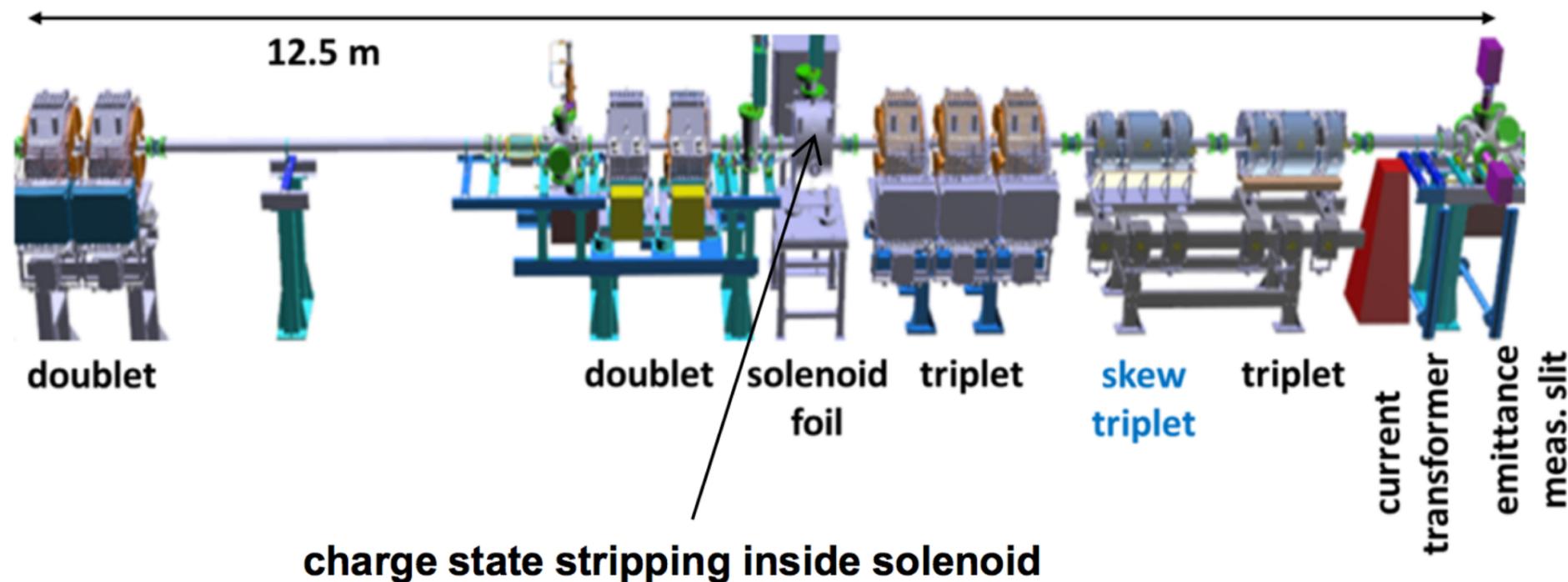


**Re-partitioning** of beam emittances **increase** efficiency

Beam flatness amount is controlled by solenoid field

Twiss-parameters are preserved

### EMTEX Beam line

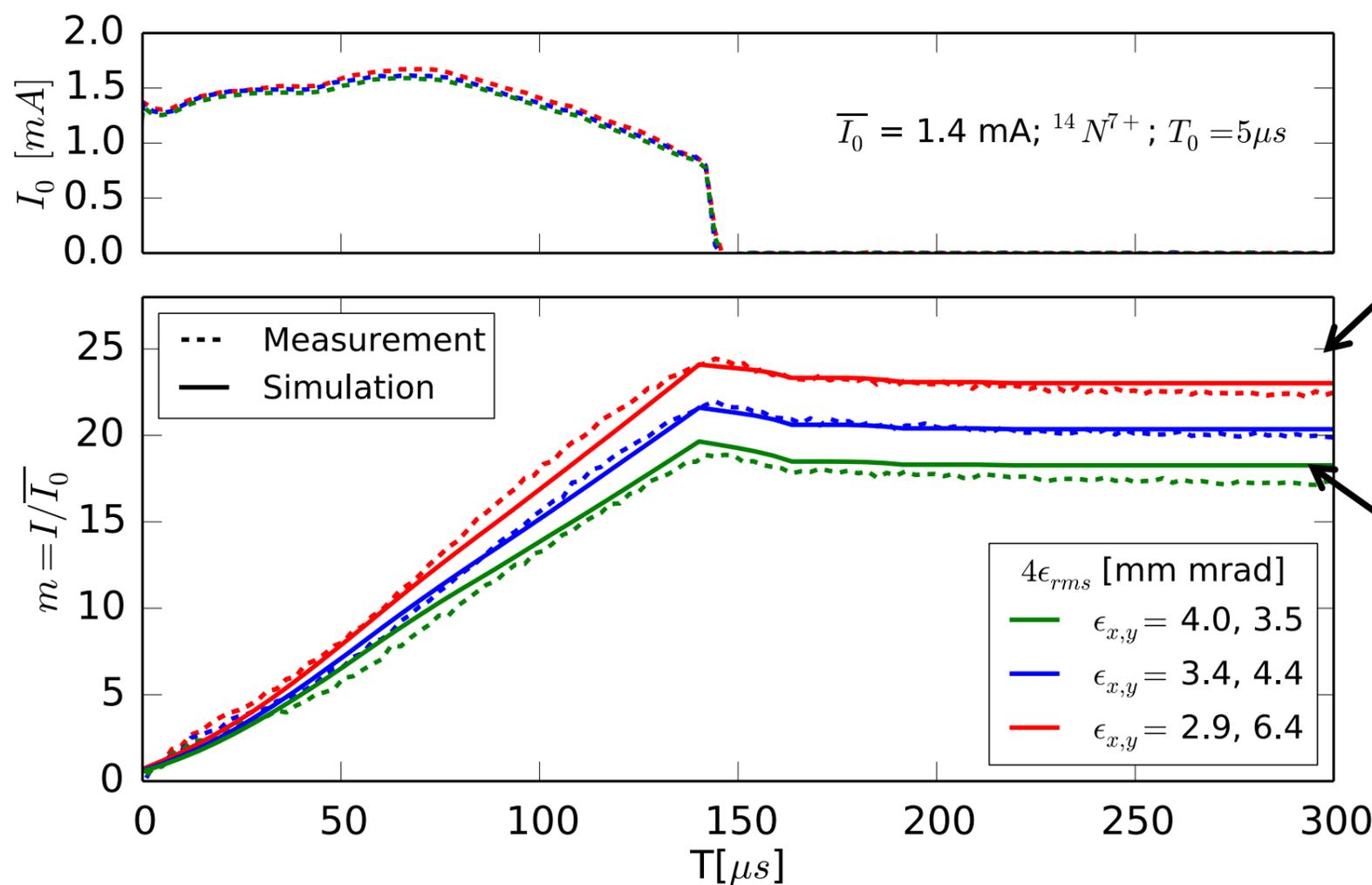


[6] L. Groening et al: Phys. Rev. Lett. 113 264802 (2014)

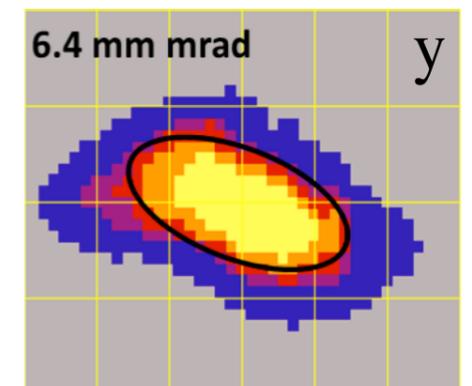
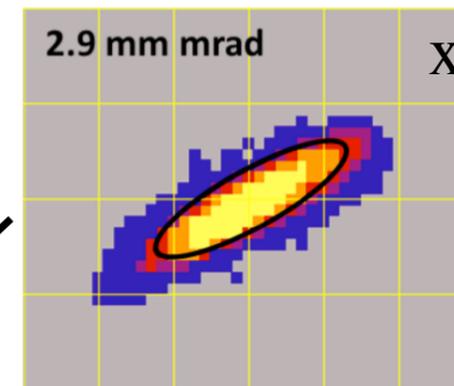
# Implementation and validation

MTI has been implemented in pyorbit code [7]

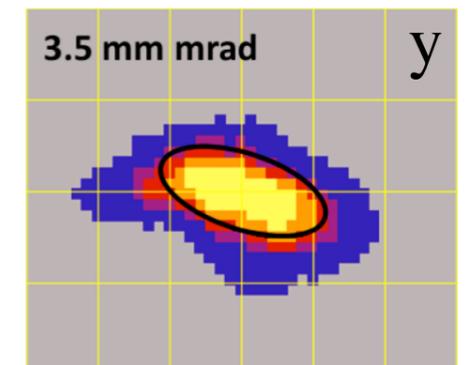
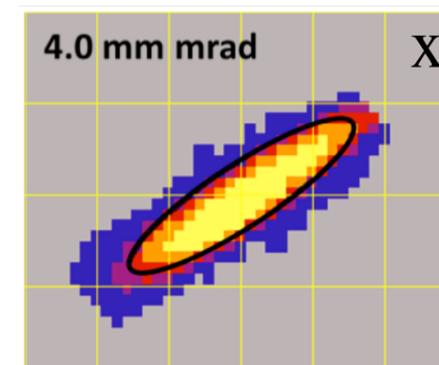
MTI performance has been measured as a function of injector emittance [8].



flat beam



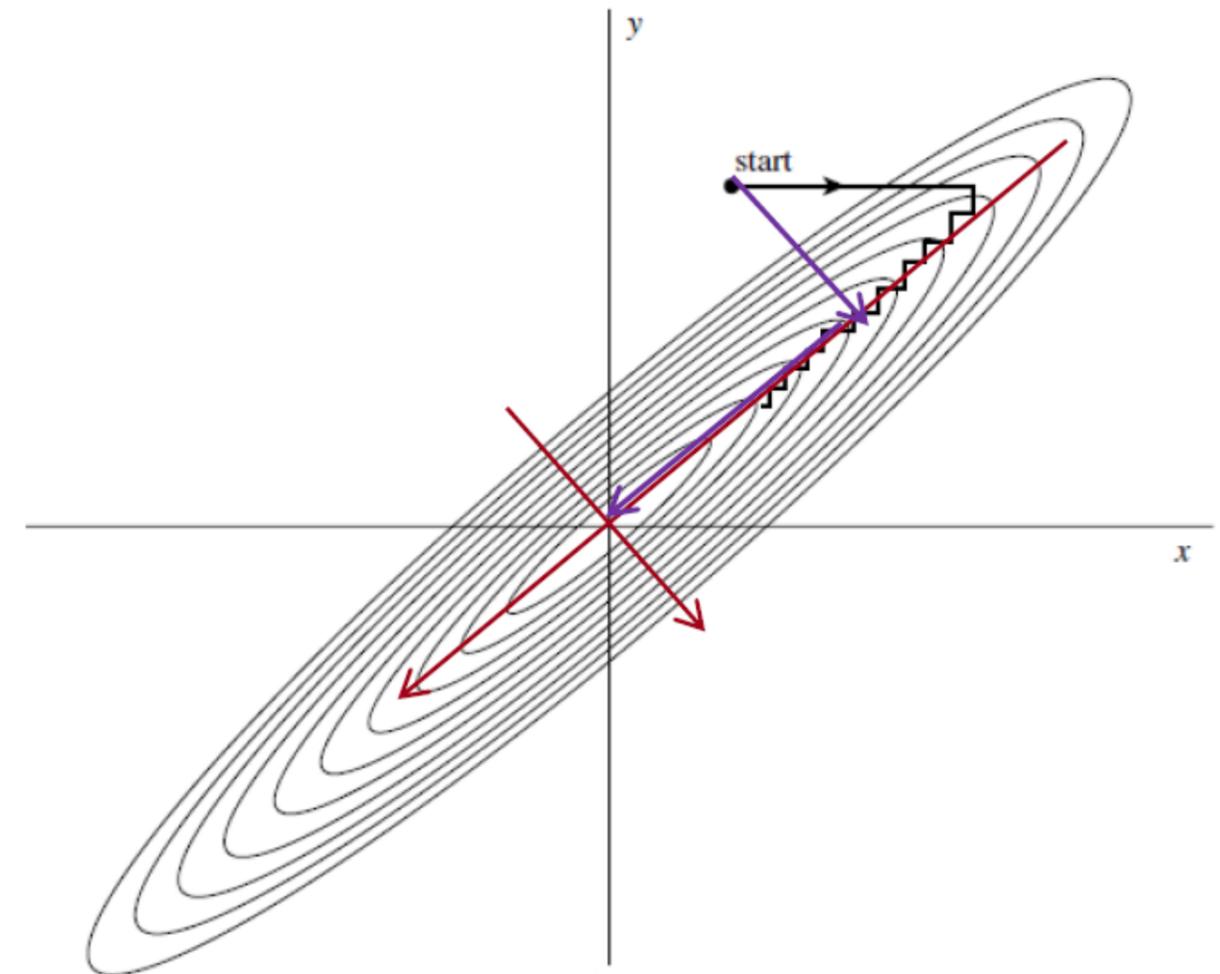
round beam



**Excellent** agreement between simulation and measurement!

[7] <https://github.com/PyORBIT-Collaboration>, [8] S. Appel et al: Nucl. Instrum. Methods A 866 (2017), pp. 36-39,

- Proposed by Michael J. D. Powell in 1964 [2]
- The function need not be differentiable, and **no derivatives** are taken.
- Pattern or Direction Search Methods
- Powell's method can update the directions using past search results to develop a conjugate set.
- Only conjugate direction sets are be used to avoid infinite rotation in a circle.



- 1D optimizer with multi variables

[2] M.J.D. Powell. Comput. J., 7, 155–162, 1964. doi: 10.1093/comjnl/7.2.155

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