NEW CERN PROTON SYNCHROTRON BEAM OPTIMIZATION TOOL

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Abstract: This paper describes a new software tool recently developed at CERN called "New CPS Beam Optimizer". This application allows the automatic optimization of beam properties using a statistical method, which has been modified to suit the purpose. Tuning beams is laborious and time-consuming, therefore, to gain operational efficiency, this new method to perform an intelligent automatic scan sequence has been implemented. The application, written in JavaFX, uses CERN control group standard libraries and is quite simple. The GUI is user-friendly and allows operators to configure different optimisation processes in a dynamic and easy way. Different measurements, complemented by simulations, have therefore been performed to try and understand the response of the algorithm. These results are presented here, along with the modifications still needed in the original mathematical libraries.

ACCELERATOR, BEAM, TUNING, PARAMETERS, FUNCTION

CERN accelerator complex is a succession of machines that accelerate particles to increasingly higher energies. Beam tuning is the process where operators change accelerator beam parameters in order to minimize or maximize beam observables. Tuning different parameters vs one or more detectors can be compared to a numerical analysis concept where optimization is devoted to the study of the theory and methods to search the smallest or largest value of a function:

$$\min_{x \in X} f(x) \quad \text{or} \quad \max_{x \in X} f(x)$$

where:

- $f: \mathbb{R}^n \to \mathbb{R}$ is the multivariable function
- $X \subseteq \mathbb{R}^n$ is the set of possible solutions

SOLUTION PROPOSED, HW & SW LIMITS, CONVERGENCE CRITERIA

Nelder Mead algorithm is believed to properly fit the needs of beam operations at CERN. The point x_i (in $\{x_1, x_2, \dots, x_{n+1}\}$ is replaced by a set of values of the n beam parameters $\{x_{i,1}, x_{i,2}, \dots, x_{i,n+1}\}$ to be optimized and the function by the beam observable:

$$\begin{gathered} x_1 = \{x_{1,1}, x_{1,2}, \dots, x_{1,n+1}\} \\ x_2 = \{x_{2,1}, x_{2,2}, \dots, x_{2,n+1}\} \\ \dots \\ x_n = \{x_{n,1}, x_{n,2}, \dots, x_{n,n+1}\} \end{gathered}$$

Some modifications with respect to the original method have been adopted. The first important one was to add constraints with upper and lower bounds for all beam parameters $x_{i,j}$, ($\forall j$ and $1 \le i \le n$). This is an essential condition due to HW limits in the different devices (imposed by the power supplies' working range) and to SW limits given by different possible instabilities and safety problems that could lead to beam losses.

The second modification adopted was to add specific convergence criteria's in order to avoid the possibility to end up in a local minimum/maximum. For example, a way of restarting the algorithm after a certain number of useless attempts has been added.

Simulations have been made, successfully checking the behaviour of a routine implemented for the maximization of a double Gaussian function in $\mathbb{R}^2$.

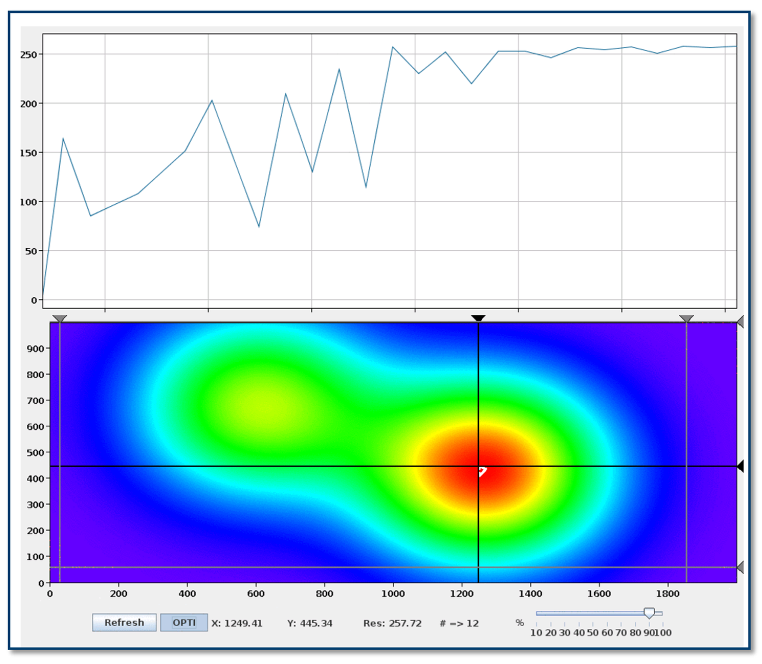
$$f(x,y) = k_1 \cdot e^{-\left(\frac{(x-x_1)^2+(y-y_1)^2}{2\cdot(\sigma_1)^2}\right)} + k_2 \cdot e^{-\left(\frac{(x-x_2)^2+(y-y_2)^2}{2\cdot(\sigma_2)^2}\right)}$$

Random data

$k_1\ k_2\ x_1\ x_2\ y_1\ y_2\ \sigma_1\ \sigma_2$

Input parameters:

- Initial "position"
- Max step size
- Convergence value
- x, y Limit

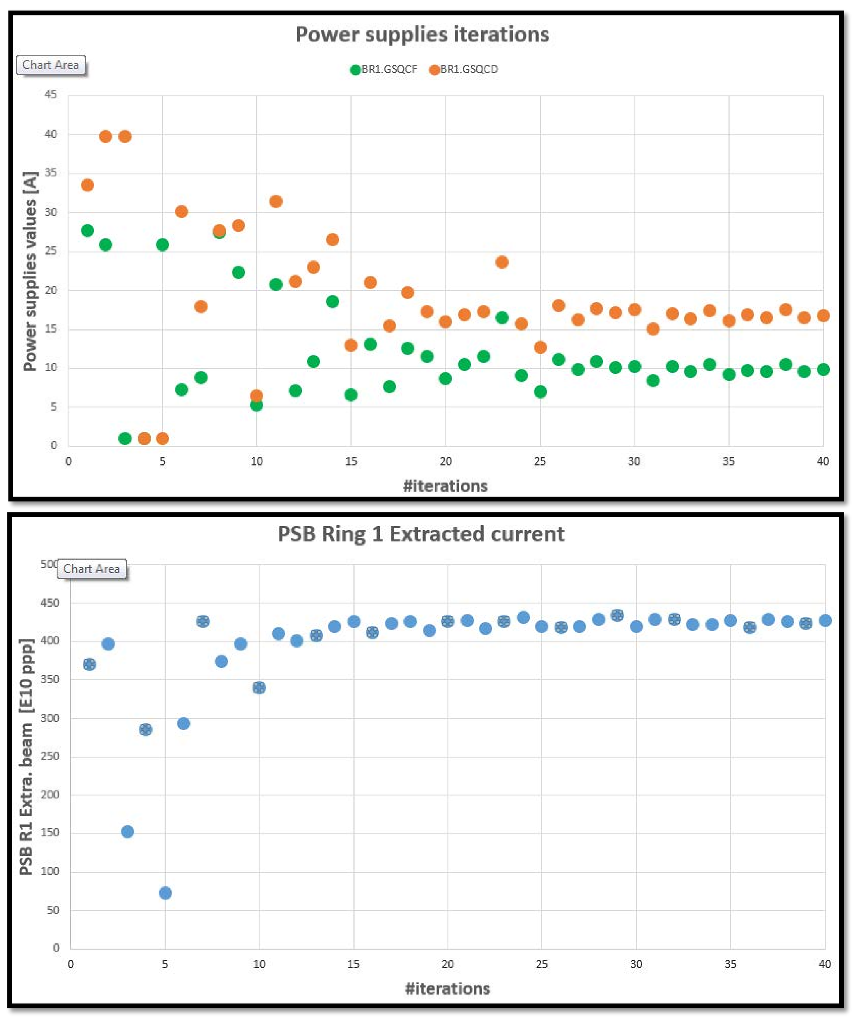


MEASUREMENTS

In the PSB, the horizontal and vertical tune of the machine (Q_h and Q_h) – the number of betatronic oscillation for one turn in horizontal and vertical planes - are defined by the main quadrupoles. At low energy, when the proton density is too high in a small space the particles reject themselves. This effect is called "space-charge". Space-charge effect can alter the Q_h and Q_h of the machine, inducting tune spread and leading to instabilities or undesired blow-up of important beam parameters, such as the transverse emittance. The smaller the emittance, the higher the brightness of the beam. To compensate for these effects, one has to balance the crossing of resonances with proper multipole setting. The control of the tune is flexible in the PSB and can be adapted for specific beam types using additional and independent magnet trims called Q-Strips.

These will bring a small correction called ΔQ_h and ΔQ_h to the tune of the machine. With the new optimization tool, several tests have been performed using the Q-Strips, in order to maximize the extracted intensity of specific beams.

Another type of measurements to test more intensively the robustness and efficiency of the algorithm was performed to maximize the transmission of the injected intensity in PSB from the Linac2.

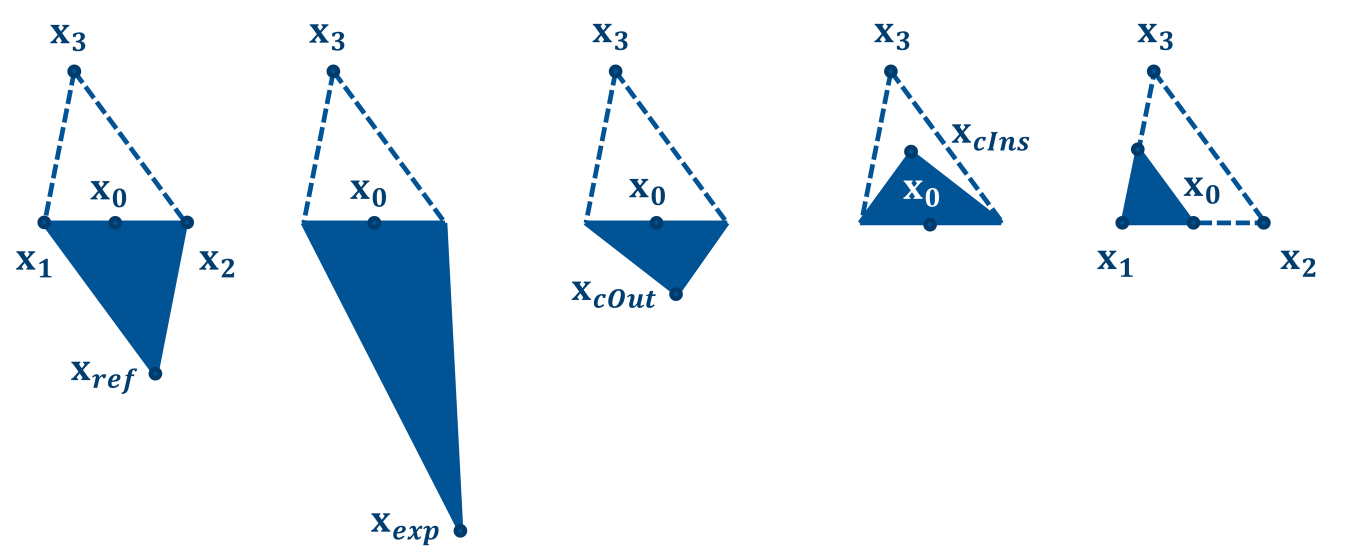


ALGORITHM, NELDER-MEAD, SIMPLEX

When the problem is looking for minimum or maximum of a function, most of the known algorithms are based on the concept of the derivative and on the gradient information. In general it is not always possible to have an analytical expression of the function (which is abstract). Direct-search methods are effective techniques in deterministic applications especially when derivatives are unavailable and they have been targeted as primary choice for the development of our new tool.

In the group of direct-search methods, the most popular one is called Nelder-Mead algorithm.

The algorithm uses a regular simplex, which is a polytope in n-dimensional space with $n+1$ vertices, each of which are connected to all other vertices (e.g. a triangle in $\mathbb{R}^2$, a tetrahedron in $\mathbb{R}^3$, etc.). In order to perform an optimization, the algorithm begins with the function's values on a set of $n+1$ points in the parameter space of n variables (simplex S^0) and it moves across the surface to be analysed in the direction of steepest ascent (for maximization) or steepest descent (for minimization) by replacing the worst vertex in the simplex with its "mirror image" across the face formed by the remaining vertices. The algorithm, while running, can change in five different ways during an iteration.



Initial simplex $S^0 = \{f(x_1), f(x_2), \dots, f(x_{n+1})\}$

Centroid $x_0 = \frac{1}{n}\sum_{i=1}^{n} x_i$

$x_{ref} = (1+\alpha)x_0 - \alpha x_{n+1}$

$x_{exp} = x_0 + \gamma(x_{ref} - x_0)$

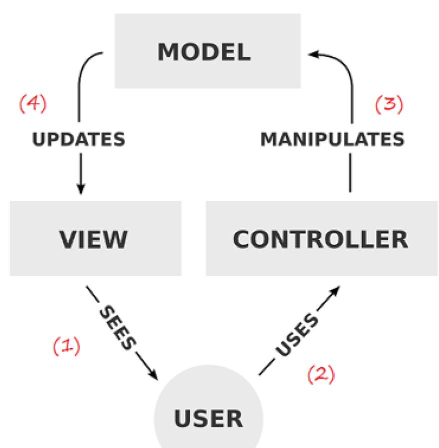
$x_{cOut} = x_0 + \beta(x_{ref} - x_0)$

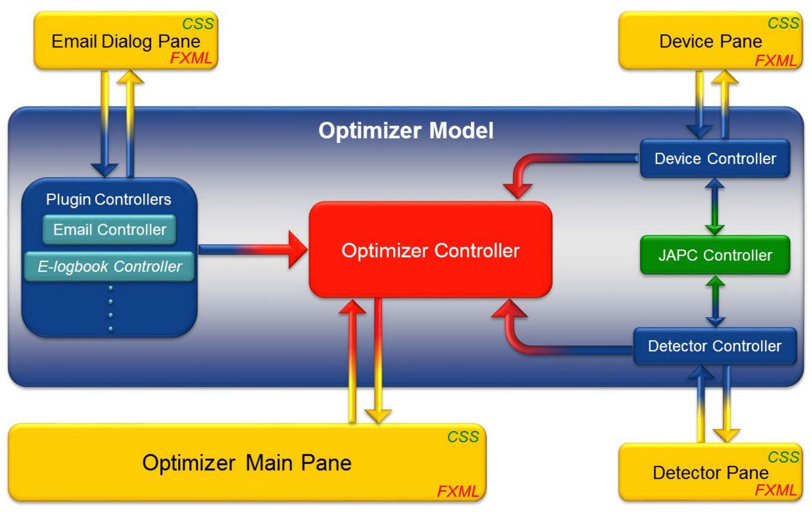
$x_{cIns} = x_0 - \beta(x_0 - x_{n+1})$

$x_i = x_1 + \delta(x_i - x_1) \quad \forall i \in [2, n+1]$

SOFTWARE APPLICATION, GUI, JAVA FX

The application program has been developed using JavaFX toolkit. The flexibility and the easy use of this programming language allowed the creation of a very robust and reliable application, respecting a very simple logic composed with a model, a view (GUI) part and a controller part.



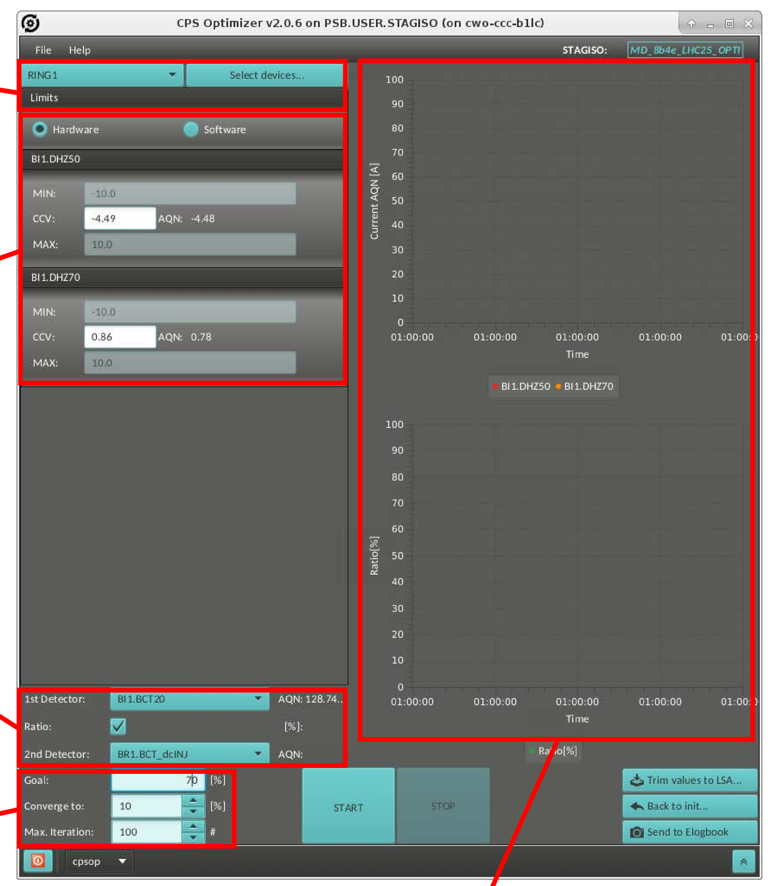


Button which opens a dialog pane with the list of devices to scan, grouped according to their physical location in the machine.

Panels showing actual values and acquisition data. For each device it is possible to select either hardware or software limits to be used during the scan.

Combo Box which allows to select which beam observable to monitor. It is even possible to select two observables in order to perform the optimization of ratio of beam observables.

Central part of the application:
"Goal": the value which one aims to reach in order to stop the optimization. "Converge to": once the "Goal" value is reached by the optimization, the reading of the beam observable(s) should be within a range fixed around this value as percentage of the goal value reached. "Maximum Iterations": the maximum number of iterations of the algorithm before converging. If this number is exceeded, the optimization process finishes and the application shows a failure message.



These two charts display the evolution of the optimization process while scanning devices: the top chart shows acquisition data from the selected devices and the bottom one the acquisition data from the selected observables (or their ratio).

CONCLUSION, PERSPECTIVES, FUTURE DEVELOPMENTS

A software tool has been developed targeting the operation of the CPS complex at CERN. This application allows the automatic optimization of beam properties using a statistical method. Preliminary measurements with beam in the PSB showed a fast response of the algorithm and all the tests done, agreed with expectations. Although initial measurements concur with expectations, there remains a need to implement a minimization optimization functionality and furthermore to improve the "fine tuning" of the convergence parameters in order to increase the speed of the optimization during machine operation.

From experience with this method, it is understood that the beam tuning task could often be automated and that many parameters could be auto tuned with results similar to an experienced human operator.

The plan for the future is to have a general tool which can be used across accelerators for the current and future CERN operations.

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