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ION SOURCE OPTIMIZATION USING BI-OBJECTIVE GENETIC AND MATRIX-PROFILE ALGORITHM

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Abstract

Employing the local ECR ion source of the FAIR phase 0 ion storage-ring CRYRING@ESR, we set up an IT-environment for on-line data processing and for applications accessing data available from beam-diagnostic instruments and input parameters controlling CRYRING@ESR's ion source. As a first proof of principle, we implemented a closed-loop optimization software controller based on bi-objective Genetic Optimization. As first optimization goal property we used the averaged ion beam current measured with a Faraday cup. The second goal property was a metric for the pulse-by-pulse stability of the source. This metric was derived from the time-resolved signal of the individual ion source pulses employing the relatively new Matrix-Profile Algorithm. This paper reports on the status of the data logging framework, the implementation of related software programs and the results of first tests.

INTRODUCTION

CRYRING@ESR is a heavy ion storage ring initially operated for about 20 years at the Manne Siegbahn Laboratory of the Stockholm university in Sweden [1]. In 2012 the ring hardware was shipped to GSI as in-kind contribution of Sweden to the FAIR project [2] where it became operational in 2020. Initially intended to serve as mid- to low-energy storage ring for combined heavy-ion/antiproton experiments at the FLAIR experimental complex of FAIR, it was decided to shift priorities and to install CRYRING at the end of an ion beam transfer line from the Experimental Storage Ring (ESR). Together with the changed location, CRYRING's purpose shifted and CRYRING@ESR was to become a mid/low-energy ion storage ring for precision experiments in atomic and nuclear physics. Besides the scientific use-case, CRYRING@ESR was designated to serve as a test bench for the FAIR control system which is based on the software stack of the CERN control system with specific development to adapt for FAIR requirements [3] and for "novel" software concepts in the framework of the FAIR CS.

ECR ION SOURCE AS TEST ENVIRONMENT

One unique feature of CRYRING@ESR is it's local ion source and LINAC injector which allows off-line operation of the CRYRING@ESR machine independent of the GSI/FAIR accelerator complex. To explore the idea of automated ion source optimization we performed test experiments on CRYRING@ESR's 10 GHz Electron Cyclotron Resonance ion source (ECRIS) provided by the Atomic and Molecular Physics group of the Justus-Liebig-university in Giessen [4].

The ion source together with corresponding control parameters is shown in Fig. 1. The ion source has six control parameters which influence the ion source performance and the charge state of the ions produced, see Table 1.

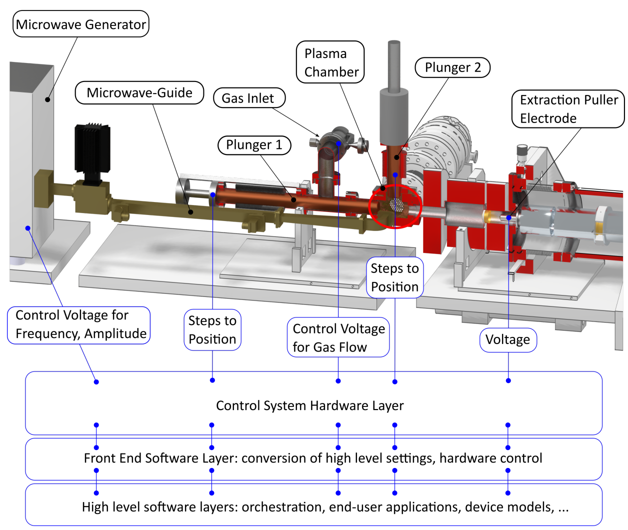

Figure 1: Illustration of the ECRIS ion source, related control parameters and FAIR CS layers. In the optimization experiments, the plunger positions were not controlled by the algorithm due to technical restrictions.

Table 1: Control Parameters of the "ECRIS" Ion Source, Their Usable Parameter Ranges and Indicator if These Have Been Used in the Optimization

Element	Param.	Range	Used
microwave	frequency	9 – 10.5 MHz	yes
microwave	amplitude	0 – 9 V	yes
gas flow	ctrl voltage	0 – 10 V	yes
extraction puller	voltage	0 –35 kV	yes
plunger 1	position	0 – 170.0 A	no
plunger 2	position	0 – 170.0 A	no
Sum of parameters controlled by optimizer: 4			

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The ECRIS produces a cw ion beam which is converted to pulses by an electrostatic chopper element positioned between the ion source and an mass-separator magnet used for ion-species selection. Goal parameters for the optimizer algorithm were extracted from the signal from Faraday cup positioned behind the mass separator magnet. The analog signal from Faraday cup was digitized into a time-resolved signal with 10 MHz sample rate, 13 kilo-samples per pulse. In addition to the time-resolved signal, the FAIR CS provides the average ion beam current per beam pulse.

OPTIMIZER TECHNOLOGY / SOFTWARE STACK

Data Acquisition and Processing

Besides proving the feasibility of automated ion source optimization, the main goal of this project was to set up am IT-framework enabling closed-loop controller development optionally involving non-JAVA programs and data processing code integrating into the FAIR Control System environment.

For the purpose of this project we set up an IT-infrastructur shown in Fig. 2. The digitized signal of the Faraday cup is made available for consuming code through the FAIR CS JAPC-layer. Our optimizer software subscribes to updates of this data and sends it to a Kafka message proker. The data arriving at the broker is picked up by an Apache Camel based routing engine transferring the data to an InfluxDb time-series database where it is stored for further processing and visualization. The Optimizer program receives data on the one hand from the JAPC-layer, on the other hand from a Python program running matrix-profile calculations in parallel on a separate computer. Finally, as soon as the result of the matrix-profile calculation becomes available to the optimizer (typically after 10 seconds) it creates a new settings data set and sends the data to the ion source control hardware.

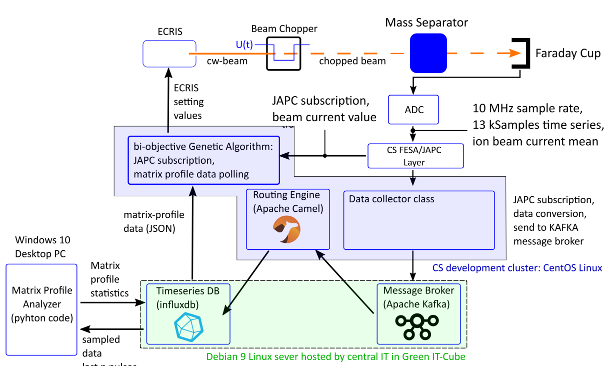

Figure 2: Schema showing the layout of the IT-infrastructure set up for the bi-objective optimizer project and the related data flow.

Genetic Algorithm

Building on earlier experiments with Genetic Algorithms [5], we implemented a JAVA computer program integrating into the FAIR control system using the "Jenetics" JAVA library [6] which was available in the version 6.1.0 at the time of performing the experiments described herein. Where we optimized one objective in the earlier versions of the program, it was upgraded such that multi-objective optimization can be performed. The multi-objective fitness function optimizes the Pareto-front of the N goal parameters, meaning a balanced optimum of all the goal parameters.

Matrix-Profile Algorithm

The matrix-profile algorithm is a relatively new algorithm for analyzing time series data [7] without explicit parameterization of a function for analysis. It is designed to provide metrics on "motifs" (re-appearing patterns in the series) and "discords" (deviations from a strictly periodic signal in the time series) by calculating the z-normalized Euclidean distance for all $m - l$ subsets (length l) of the total data set (length m). The z-normalized Euclidean distance is given for two time series of the same length m $\mathbf{x} = x_1, ..., x_n$ and $\mathbf{y} = y_1, ..., y_n$ [8]:

$$D(\hat{\mathbf{x}}, \hat{\mathbf{y}}) = \sqrt{2m[1 - \underbrace{\frac{\sum_{i=1}^{m} x_i y_i - m\mu_x\mu_y}{m\sigma_x\sigma_y}}_{\text{correlation coefficient } r_{xy} \in [-1,1]}]}. \quad (1)$$

With the following replacements

$$\hat{\mathbf{x}} = \hat{x}_1, ..., \hat{x}_n, \text{ where } \hat{x}_i = \frac{x_i - \mu_x}{\sigma_x} \text{ and}$$
$$\hat{\mathbf{y}} = \hat{y}_1, ..., \hat{y}_n, \text{ where } \hat{y}_i = \frac{y_i - \mu_y}{\sigma_y},$$

$\mu_{x,y}$ is the means and $\sigma_{x,y}$ as the standard deviations of the samples $\mathbf{x}$ and $\mathbf{y}$ respectively. The correlation coefficient of two given series and the z-normalized Euclidean distance are anti-proportional to each other: low z-normalized Euclidean distance values indicate strong correlation, high values low correlation.

The matrix profile algorithm calculates for the $m - l$ subsets of a time series data set of length m, $m - l$ times the z-normalized Euclidean distance by sliding each subset over the remaining data set and calculating the distance value for each slide step. For each subset, the result of the algorithm is the minimum value of the $m - l$ distance calculations and the final output is a vector of $m - l$ distance values.

For our purposes, the information "source runs stably or not" can be extracted by observing the statistical properties of the matrix-profile data-array: if the signals of the individual ion-source pulses change significantly, the matrix-profile exhibits large fluctuations and resulting from that a large variance as it is very sensitive to changes in the shape of the signal, whereas matrix profile statistics will show small values at stable source operation.

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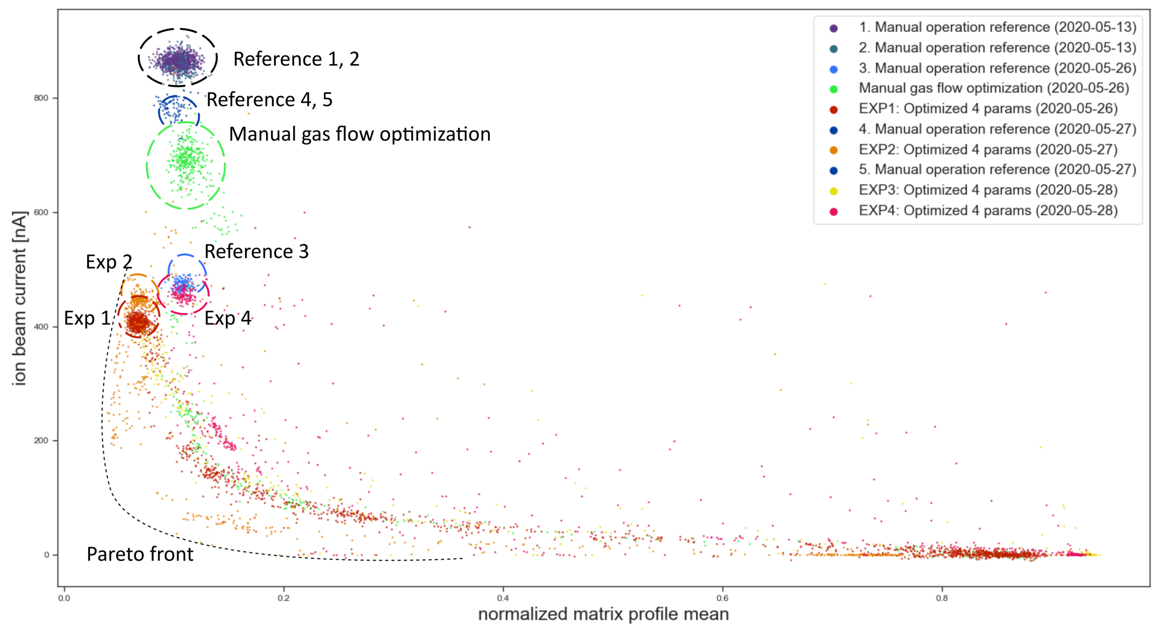

Figure 3: Plot of mean ion beam current against normalized matrix profile mean $(D(\hat{x},\hat{y})/\sqrt{2m})$. The data points plotted in blue were collected during normal ion source operation of Ne^{7+} at an acceleration voltage of 28.6 kV and the source tuned by an ion source expert. The other colors indicate data from optimization experiments. The order of the elements in the legend is given by the order in time of the individual data sets.

RESULTS

During feasibility tests at the end of a commissioning run in June 2020, we performed five experiments, each with different settings for the genetic algorithm parameters: population size, convergence criterium, mutation parameter, survivor selection criteria, etc. Optimizer convergence typically was reached after 300 to 600 steps corresponding to 50 to 100 minutes of parameter scanning.

As can be seen in Fig. 3, the two parameters "beam current" and "matrix profile mean" exhibit Pareto-front defining the accessible working range for ion source operation. In terms of ion beam current, the optimizer falls short compared with manual optimization, but shows better results in terms of shot-by-shot ion source stability. Where we can show only qualitative results at present state, further investigations with better boundary conditions are needed to get to quantitative results.

CONCLUSION, SUMMARY

In the scope of this project, we set up an IT-infrastructure which allows building closed loop controllers based on data available in the framework of the FAIR control system. As a proof-of-principle, we built an optimizer based on a Genetic Algorithm able to do bi-objective optimization on competing goals. As a new element, we used the matrix-profile algorithm to calculate a model-independent, single-number metric to qualify the stability of operation of the local ECR ion source of CRYRING@ESR. First experiments show the feasibility of the methods applied and show promising results with room for improvement when applied for automated ion source optimization. Besides developing the automated optimization case further, matrix-profile showed to be a useful tool which could be applied to other use cases such as qualifying the stability of other accelerator-related observables.

REFERENCES

[1] K. Abrahamson *et al.*, "CRYRING - a synchrotron, cooler and storage ring", *Nucl. Instr. Meth. B*, vol. 79, pp. 262-272, 1993. doi:10.1016/0168-583X(93)95341-2

[2] H. H. Gutbrod, "International Facility for Antiproton and Ion Research (FAIR) at GSI, Darmstadt", *Nuclear Physics A*, vol. 752, pp. 457–469, Apr. 2005. doi:10.1016/j.nuclphysa.2005.02.137

[3] R. Huhmann *et al.*, "The FAIR Control System - System Architecture and First Implementations", in *Proc. 14th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'13)*, San Francisco, CA, USA, Oct. 2013, paper MOPPC097, pp. 328-331.

[4] R. Trassl, W. R. Thompson, F. Broetz, M. Pawlowsky, R. W. McCullough, and E. Salzborn, "Development of a 10 GHz "Multi-Mode" ECR, Ion Source for the Production of Multiply Charged Ions from Metallic Elements", *Physica Scripta*, vol. T80, no. B, p. 504, 1999. doi:10.1238/Physica.Topical.080a00504

[5] S. Appel, W. Geithner, S. Reimann, M. Sapinski, R. Singh, and D. Vilsmeier, "Application of nature-inspired optimization algorithms and machine learning for heavy-ion synchrotrons", International Journal of Modern Physics A, vol. 34, no. 36, p. 1942019, Dec. 2019. doi:10.1142/s0217751x19420193

[6] Jenetics advanced genetic algorithm, http://jenetics.io

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[7] A. Van Benschoten, A. Ouyang, F. Bischoff, and T. Marrs, "MPA: a novel cross-language API for time series analysis", *Journal of Open Source Software*, vol. 5, no. 49, p. 2179, May 2020. doi:10.21105/joss.02179

[8] *The First Matrix Profile Tutorial - Part 2*, E. Keogh, A. Mueen, Riverside, CA, USA, 2017; https://www.cs.ucr.edu/~eamonn/Matrix_Profile_Tutorial_Part2.pdf