ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR60

ALGORITHMIC ACCESS TO BEAM CONTROL AND BEAM DIAGNOSTICS AT COSY JÜLICH

J. Hetzel*, A. Awal[1], R. Gebel, V. Kamerdzhiev
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
I. Bekman[2], C. Deliege, J. Pretz[1], M. Simon, M. Thelen
Institut für Kernpyhsik, Forschungszentrum Jülich, Jülich, Germany
R. Modic, Z. Oven, Cosylab, d.d., Control System Laboratory, Ljubljana, Slovenia
[1]also at III. Physikalisches Institut B, RWTH Aachen University, Aachen, Germany
[2]now at ZEA-2, Forschungszentrum Jülich, Jülich, Germany

Abstract

During the last years of operation of the COSY facility, significant improvements were made in beam diagnostics and beam control. Many systems have been upgraded from a Tcl/Tk based control system to EPICS. One of the advantages of EPICS is the coherent communication via Process Variables (PVs). This allowed us not only to control the synchrotron and its injection beam line (IBL) through GUIs but also allowed us to control the beam with algorithms. In our case, these algorithms covered a range of applications from variation of the currents of the electromagnets up to more advanced techniques of AI/ML such as Bayesian Optimization or beam control with Reinforcement Learning. Due to the unified nature of the PVs, the algorithms can be fed with a plethora of input parameters such as beam positions, beam current, or even live images of a camera.

COSY and the EPICS Control System

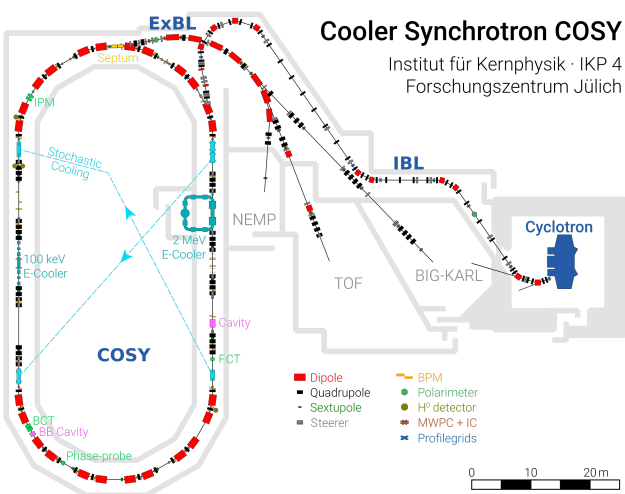

Figure 1: The COSY facility at the research centre in Jülich (FZJ), depicted are the cyclotron (right), the cooler synchrotron COSY (left), the interconnecting injection beam line IBL, and the extraction beam lines ExBL.

The Cooler Synchrotron COSY [1] in Jülich, Germany, delivered proton and deuteron beams to its international users from 1993 until 2023. The COSY facility consists of several interconected components, cf. Fig. 1: the polarized or unpolarized proton (deuteron) beam, generated by the ion sources, is preaccelerated by the cyclotron JULIC to a momentum of 294 MeV/c (536 MeV/c). It is then guided to the synchrotron via the injection beam line (IBL), where it is injected by multiturn stripping injection. In COSY, the beam can be accelerated to a momentum up to 3700 MeV/c. In the mid 2010s a major upgrade of the control system was initiated. As a part of this upgrade, the control system was switched from tcl/tk to EPICS [2] for several accelerator elements. In the case of COSY, the EPICS Framework provides an abstraction of hardware and its properties into PVs in a server-client manner. The Input Output Controller (IOC) is the server part responsible for interaction with hardware components and/or any software process (eg. state machine, algorithm implementation) needed to control such hardware. It also exposes all these properties to the clients (like GUIs, archive service, alarm service, or higher-level applications for control) in form of PVs that are accessible through the network. This provides any user (operators, machine physicists, control engineers) with network access rights to monitor and control the devices. By following facility-wide naming convention for PVs when implementing the control system, the users got a unified interface to all devices with complete abstraction of different hardware implementations. An overview over the implementation of the upgrade is presented in [3].

Use Case

The aforementioned upgrade enabled the implementation of different algorithms for automatic beam line control. This contribution focuses on developments related to the injection beam line and the injection process, although the application of algorithms is also done for the COSY ring, for instance by the automated orbit correction, which is described in more detail in [4]. Within the IBL, negatively charged particles are transported from the cyclotron to COSY. The injection process is done via multi-turn stripping injection, during which the electrons are removed by a stripping foil (TUM). The closed orbit in the ring is locally moved to the edge of the stripping foil by means of three bumper magnets. During the injection process, the acceptance of COSY is filled by a 20 ms long beam pulse from the IBL. The beam

* j.hetzel@gsi.de

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR60

is injected during the downwards ramp of the orbit bump. The reduction of the bump amplitude is also beneficial as it moves the stored beam away from the stripping foil, thus preventing beam loss due to multiple scattering with the foil. A successful injection of the beam into COSY is crucial for the whole downstream chain. Among the most important factors to achieve this are the transfer of particles through the IBL, the bumper settings, and the position, size and angle of the incoming beam at the TUM location. The objective of the IBL optimisation is to store a maximum amount of beam in COSY. The setting of both, the IBL and the bumpers, also influences the quality of the stored beam, which in turn affects the bunching and acceleration process. Therefore a more advanced measure of the quality of the IBL settings is the intensity of the accelerated beam for a given acceleration ramp.

Diagnostics The intensity of the stored beam in COSY is measured by means of a beam current transformer (BCT). Several beam diagnostics elements are located within the injection beam line, including beam cups to measure the beam intensity, with one beam cup located at the beginning of the IBL, one after the last bent section and one in between. Furthermore the evolution of the TUM current provides qualitative information in regard of the injection process. By replacing the TUM foil with a fluorescence screen, the location and dimensions of the beam spot can be directly recorded with a video camera.
Both integrations benefit from the EPICS community-provided device supports based on corresponding selected hardware. Beckhoff hardware is used for collecting analogue values of BCT readback with corresponding support provided by Diamond-developed EtherCAT master [3]. The TUM fluorescence screen camera is integrated into EPICS via the AreaDetector [5] module, which supports various camera models used throughout the EPICS community.

Beam Control The beam inside the IBL is controlled by dipoles, quadrupoles, and steerers, each of which is a normal conducting magnet. In 2021, the control of the corresponding power supplies was upgraded to EPICS. The quadrupoles and dipoles are grouped in families, where each family of magnets is connected to only one power supply.
Device support was developed and integrated into the IOC for each magnet type (dipole, quadrupole, steerer) and corresponding power supply. One of the requirements for algorithmic access and control over these devices was a unified, implementation-independent interface. This was achieved by identifying which parameters need to be accessible by the algorithm (eg. current set-point and read-back, or enable/disable) and providing common pattern for PVs and behaviour across all power supply device support implementations.

Algorithms

Bump Calculation and Application To achieve a closed orbit bump with the three injection bumpers, the corresponding setting is calculated automatically from the current settings of the COSY magnets using MAD-X [6]. A newly developed EPICS GUI allows the operator to transfer the setting and apply it to the bumpers.

Digital Twin of the IBL In order to facilitate software developments at the real IBL, a simulation of the beam line was realized as an EPICS soft-IOC. This digital twin [7] mimics the PVs of all power supplies, as well as the measurement of intensity with beam cups. The simulation includes ramping times of magnets and measurement noise. The soft-IOC initiates a particle tracking of 10,000 particles with the PTC module of MAD-X. Every two seconds a new tracking with randomised initial phase-space coordinates is initiated. This period corresponds to the minimal time of the injection cycle of COSY. The soft-IOC is executed locally on a developer's computer. The names of the PVs differ from the corresponding names of the real IBL by a preceding "SIM:", for example "SIM:IBL:SH81:DA:SP" instead of "IBL:SH81:DA:SP". This approach enables developers to write production code for the real IBL and test their code for functionality independently of the availability of beam time at the accelerator, through a simple extension of the PV-names.

Random Variation As a proof of concept, a random variation of the IBL power supplies has been implemented. Here, the IBL is initialised with a standard setting, where at least some amount of beam is transferred to COSY. Now, a magnetic element is randomly chosen. The current of this element is then varied, starting from the original value, by reducing or increasing it by a given step size until a maximum in the transferred intensity as measured at COSY is identified. In order to reduce the influence of noise, an average is calculated based on several shots from the cyclotron with the same settings. The optimal value is then estimated by fitting a polynomial of second order to the measured data points. The power supply for the selected element is then set accordingly and the algorithm continues with the next element, which is, again, randomly chosen. Each time an element that has already been optimised is selected, the step size of the variation for this element is reduced by a certain percentage. This method emulates the typical optimization process, which is carried-out manually by the COSY operators. It yields comparable outcomes.

Bayesian Optimizer The previous method is prone to get stuck in local minima, which is why a Bayesian Optimizer is employed to automatically optimise the magnet settings of the IBL [8]. As with the random variation, the objective is to achieve a maximal transmission through the IBL. Unlike the random variation, the Bayesian Optimizer is capable of varying all elements that have been selected for optimisation simultaneously. To prevent the algorithm from creating a complete beam loss, the setting is checked in a model calculation with MAD-X. Only if the resulting beta-functions are sufficiently small in the whole IBL, the

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR60

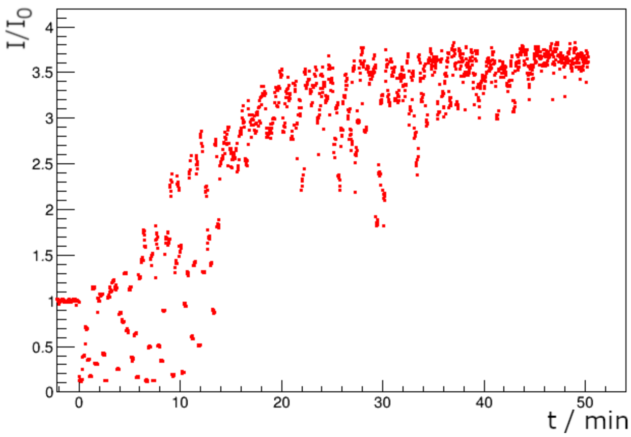

Figure 2: The evolution of the stored current at COSY during application of the Bayesian optimization. The current I is normalised to the initial current I_0.

algorithm is allowed to set the elements' currents. During run-time, the Bayesian Optimizer creates a surrogate model of the transmitted intensity as a function of all settings. The choice of meta-parameters determines whether the algorithm favours exploration (regions in parameter space with high uncertainty) or exploitation (regions with high transmitted intensity). Following successful tests with the Bayesian Optimizer (see Fig. 2), the algorithm was used during the machine development phase of several beam times at COSY. A significant benefit of the implemented algorithm utilising the EPICS interface is that it can be adopted to any PV that is related to the injection process, provided that the quantity has a distinct extremum, which can be used to quantify the quality of the current setting. Target quantities that were used at COSY comprise the transmission to only a part of the IBL as measured by the corresponding beam cup, the transmission through the whole IBL as measured by the current through the stripping foil, the latter as measured by the COSY BCT after injection and as measured by the same BCT after injection, bunching and acceleration. A typical optimization takes about one hour until it reaches convergence. The algorithm's flexibility allows it to be applied at any other facility, where a medium number of parameters (~ 20) are to be optimized.

Reinforcement Learning Another method for optimizing the injection process is to reproduce the position and width of the beam in phase space for each injection, independently of the beam as delivered from the cyclotron. To achieve this, a reinforcement learning agent has been developed and tested. Unlike numerical optimization methods, a reinforcement agent is able to build a concept of the problem it is trained on. This allows the agent to make targeted exploration and take more precise actions, resulting in a faster convergence as compared to numerical methods. This agent is applied to the last section of the IBL, with the remainder of the IBL being optimised separately by the Bayesian Optimizer. The agent is trained on model simulations (MAD-X)

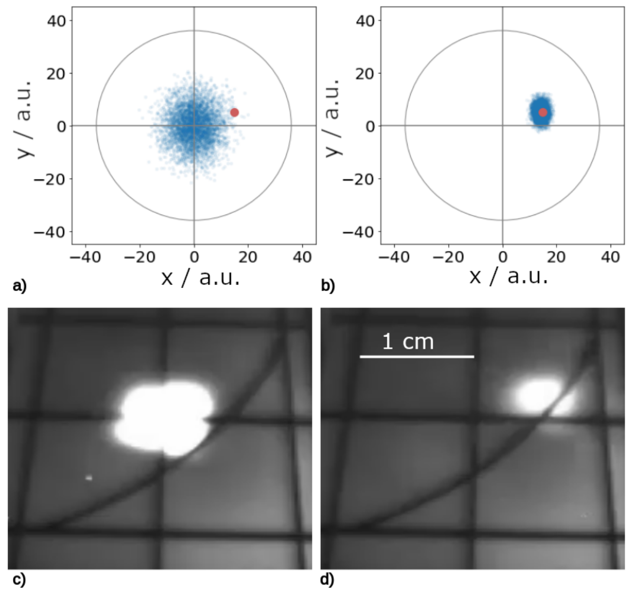

Figure 3: Example for an execution of the reinforcement learning agent [9] in simulation (a and b) and as applied at the IBL (c and d). The figures show the distribution of particles at the viewer before (a and c) and after optimisation by the agent. The orange dot in a and b denotes the desired position as set by the operator.

to steer the beam and control its width and height as recorded by the viewer at the injection position. As we rely on a single viewer, the agent can only control the spatial position and extend. The successful transfer from simulation to the real operation has been ensured by domain randomisation and demonstrated in a dedicated beam-time at COSY [10, 11], see Fig. 3.

Summary and Outlook

The upgrade to EPICS facilitated the development of software that autonomously controls parts of the accelerator. Following the successful testing of multiple algorithms, they were subsequently integrated in the regular operation at COSY, where they assist the operators in optimising the beam intensity and quality. All tested applications demonstrate the potential for utilisation at other facilities, such as the FAIR facility.

REFERENCES

[1] R. Maier *et al.*, "Cooler synchrotron COSY", *Nucl. Phys. A*, vol. 626, iss. 1-2, pp. 395–403, Nov. 1997. doi:10.1016/S0375-9474(97)00562-9

[2] Experimental Physics and Industrial Control System (EPICS), https://epics-controls.org

[3] C. Boehme *et al.*, "Challenges of the COSY Synchrotron Control System Upgrade to EPICS", in *Proc. ICALEPCS'23*, Cape Town, South Africa, Oct. 2023, pp. 561–564. doi:10.18429/JACoW-ICALEPCS2023-TUPDP028

[4] M. Simon *et al.*, "COSY Slow Orbit Feedback System", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1802–1805. doi:10.18429/JACoW-IPAC2017-TUPIK050

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR60

[5] AreaDetector, https://areadetector.github.io/master/index.html

[6] MAD-X: Methodical Accelerator Design, https://madx.web.cern.ch

[7] J. Hetzel, "The IBL Simulator - A Digital Twin for the IBL", Institut für Kernphysik - COSY, Annual Report, p. 63, 2023.

[8] A. Awal, J. Hetzel, R. Gebel, V. Kamerdzhiev, and J. Pretz, “Optimisation of the injection beam line at the Cooler Synchrotron COSY using Bayesian Optimisation”, *J. Instrum.*, vol. 18, no.4, p. P04010, Apr. 2023. doi:10.1088/1748-0221/18/04/P04010

[9] A. Awal, J. Hetzel, and J. Pretz, “Injection optimization via reinforcement learning at the cooler synchrotron COSY”, in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 2874–2876. doi:10.18429/JACoW-IPAC2023-WEPA098

[10] A. Awal *et al.*, "Injection Optimization at Particle Accelerators via Reinforcement Learning: From Simulation to Real-World Application", presented at the IPAC'24, Nashville, TN, USA, May 2024, paper TUPS11, this conference.

[11] A. Awal *et al.*, "Injection Optimization at Particle Accelerators via Reinforcement Learning: From Simulation to Real-World Application", manuscript in preparation.