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CHALLENGES OF THE COSY SYNCHROTRON CONTROL SYSTEM UPGRADE TO EPICS

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Abstract

The COSY (COoler SYnchrotron) at the Forschungszentrum Jülich is a hadron accelerator build in the early 90s, with work started in the late 80s. At this time the whole control system was based on a self-developed real-time operating system for Motorola m68k boards, utilizing, unusual for this time, IP-networks as transport layer. The GUI was completely based on Tcl/Tk. After 25 years of operation, in 20016, it was decided to upgrade the control system to EPICS and the GUI to CS-Studio, in order to e.g. allow a better automatization or automatized archiving of operational parameters. This was done together with Cosylab d. d. bit by bit while the synchrotron was in operation, and because of the complexity is still ongoing. The experiences of the stepwise upgrade process will be presented and a lessons learned will be emphasized.

INTRODUCTION

COoler SYnchrotron COSY

The COoler SYnchrotron (COSY) of the Forschungszentrum Jülich is a 184 m long racetrack-shaped synchrotron and storage ring for protons and deuterons from 300 MeV/c (protons) or 600 MeV/c (deuterons) up to 3.7 GeV/c. Built in are devices for stochastic as well as electron cooling. The stored ions can be polarized or unpolarized. COSY was commissioned in 1993.

COSY Control System

Planning of the COSY control system date back to the mid 80s [1], which the original concept visualized in Fig. 1. The control system was self developed and based on VMEbus and G64 Hardware [2]. The communication was completely based on Ethernet 10BASE5 and 10BASE2. The communication protocol is a self developed system called "Single Command - Single Response" (SCSR), having a limited amount of commands and replies.

Timing The timing system is based on Ethernet 10BASE2 using only network hubs, as they deliver a deterministic delay, unlike network switches. The timing sender sends a broadcast every ms with an ID, timing receivers configured with that ID then send out an TTL pulse. With the used hardware the delay for each timing receiver is between 100 ns to 3.2 ms upon reception of the ID. The timing system only features timing relative to the cycle start. Each timing receiver is equipped with 2 timing outputs and 12 status bits output which can used as digital output with less accuracy.

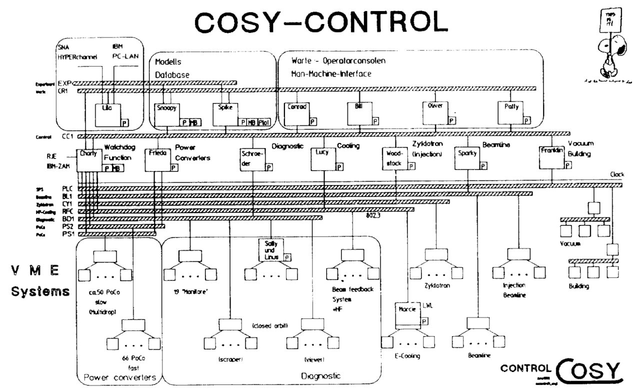

Figure 1: Original layout of the COSY control system, as described in [1].

Central Clock In order to synchronize all necessary devices, a central 8 MHz clock is distributed using as well Ethernet 10BASE2 hardware.

Function Generators The magnets at the synchrotron are controlled by self developed function generators. These controllers were designed as feed-forward controllers, because of the typical limited computing power of that time. Therefore the whole settings for one machine cycle are computed beforehand, and, after a trigger, the program is rum with only the possibility of an emergency abort. As an option, the manual control of the controllers at a pre-defined time in the machine cycle, was implemented from the beginning.

UPGRADE

Motivation

With the JEDI experiment new requirements concerning the overall RMS beam orbit deviation were introduced [3]. Therefore an automated beam orbit control system had to be developed. Furthermore, other components were identified being in need to be upgraded or to be added. One example is the analog BPM readout electronics, whose signal offsets prevented an accurate position determination especially around the 0 position. The decision was made, instead of implementing the new sub-systems and features into the old control system, to upgrade the latter in a step-wise manner, in order to avoid long down-times of the machine. In addition the following considerations were taken into account:

- Add a logging and archiving mechanism
- Use software developed and supported by a larger community
- Software and compatible hardware available without protocol adaption

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Three potential candidates were identified, EPICS, TANGO and FESA. TANGO was ruled out, as it is mainly used by electron machines. Due to the involvement in the FAIR project of the GSI Helmholzzentrum für Schwerionenforschung, Darmstadt, Germany, the FESA control system, which is used at FAIR, was another candidate. Due to the complexity of the system, and the lack of hardware available without protocol adaption, this was ruled out as well. This left EPICS, which finally was chosen as new control system environment.

This was supported by a decision that was made before the requirements for a major upgrade surfaced. There a single device family was introduced to the COSY injection beamline: Readout electronics for Harps developed by iThemba LABS, Faure, South Africa [4], which are connected via EPICS. The iThemba LABS were before going through the same process of upgrading their control system from a self-developed control system, developed since the 60s, to a modern system, and their decision was to use EPICS [5]. Due to other common projects we could learn from the experience of that project.

First Project: Orbit Correction

In order to archive the requested overall low RMS of the beam, a completely software based solution was introduced. This required the upgrade of the BPM readout with new beam processors and signal amplifiers, and the software based, online manipulation of the steerer magnets. The orbit correction algorithm itself has been presented in [6]. The first iteration was done using the analog BPM beam processors, but due to large drifts, especially around the zero-position they were soon replaced.

BPM While the actual readout and position processing of the BPMs were upgraded using the commercial available Libera Hadron from Instrumentation Technologies d.o.o., using the implemented EPICS server. To further enhance the position measurement, the decision was made to upgrade the head-on amplifiers of the BPMs as well, with an variable gain. This variable gain is used calibrate the settings of the gain to match all 4 signal pick-ups. Therefor a reference signal is generated and split by high-accuracy splitters and then fed into a calibration input on the amplifiers, using an automated method to alter the signal gain to all 4 signals to match in peak height. The amplifiers are controlled by an analog input signal. This signal is generated by the also newly introduced EtherCAT slow control system.

Magnet Control For orbit control of the circulating beam, only the steerer magnets are used. Therefore these magnets were the first to be converted to an EPICS control. Classically, the control of the magnets is done by the above described function generators. These are using a parallel hardware bus towards the magnets power supply, which then uses this hardware signal for the setting of the current. The mentioned manual control was originally implemented into the controller, but up till then never used. The initial function generators are connected by Ethernet connections and use the TCP/IP based communication protocol SCSR, the decision was made to generate an IOC for translating the EPICS communication to SCSR, for lower costs and faster implementation of the system. Within the power supply no safety is implemented, leading to damages if the power supply wold be enforced to do quick changes. This had to be taken into account when using the IOC for the online-mode. When switching from preloaded-mode to online-mode the last setting would have to be the start value for the current setting, before exiting the online-mode the current setting would have to be set to the start value of the preloaded mode, in order to avoid huge steps. This would as well have to be done in a reliable way, if there would be a fault during the cycle, leading e.g. to an emergency stop of the accelerator, when resuming operation a huge step in current settings would also have to be avoided reliably. During the usage of the beam orbit feedback IOC it was realized, that the function generators were getting unreliable when issuing a new setting faster than every 2 seconds, limiting the response time for the IOC.

EtherCAT For slow control and readback an integrated, low cost system was searched for. As an almost ready-to-use implementation is provided by the DIAMOND EtherCAT implementation [7], which again is also used at other labs like iThemba LABS or at that time planned to be used the European Spallation Source (ESS), we as well used the implementation at COSY. For the analog control of the BPM head-on amplifiers an EtherCAT installation was implemented. There the limitations of 1 kHz update rate is well over the required speed. As for each amplification setting a new calibration of the amplifiers is required, usually no machine-cycle dependent settings are used, but settings which cover the whole cycle.

Further Upgrades

With the initial introduction of the EPICS control system several other enhancements and further upgrades could be enabled.

Save & Restore and Archiving

With the EPICS control system several methods of Save & Restore and archiving are possible. For the archiever we chose ”The EPICS Archiver Appliance” [8]. Shown in Fig. 2 is the amount of archived PVs over time. With this number the stepwise approach of the transition to EPICS can be clearly seen. For the Save & Restore feature the method implemented within Control System Studio is used.

Further EtherCAD installations After the implementation of the EtherCAT system for the BPM gain control, the system was extended to other systems as well. Some implementations are:

- Readout and control of the Bergoz Parametric Current Transformer. The readout of the signal is done by a single ADC (EL3101), while the control of e.g. the range and the calibration is done via a 5V digital output, and the readback of the settings via a 5V digital input.

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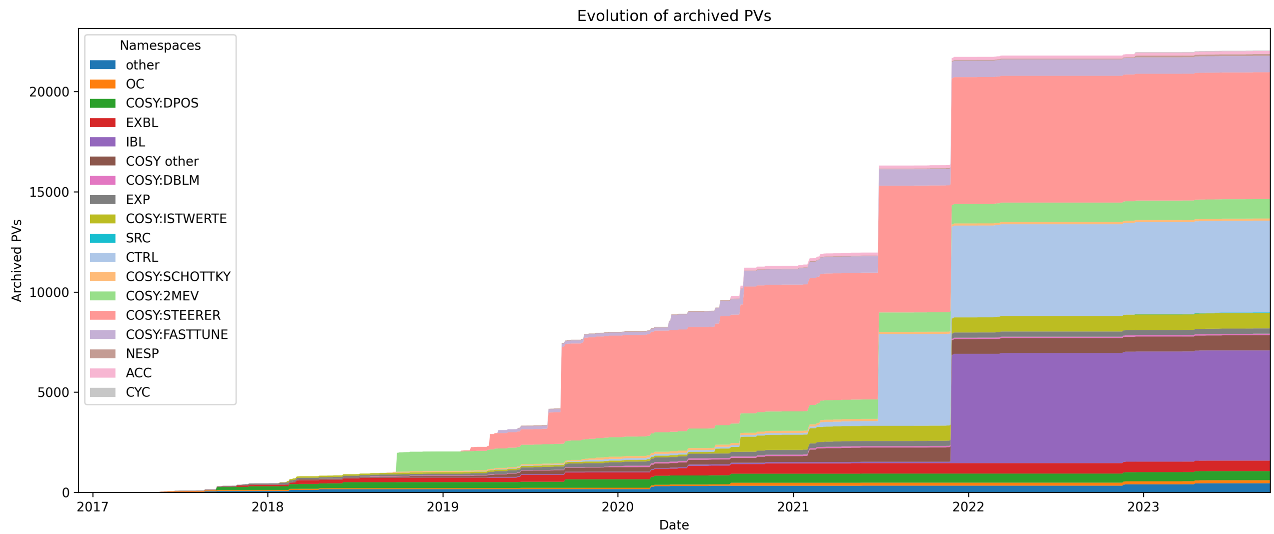

Figure 2: Evolution of the amount of archived PVs. The step-wise approach to switch the control system to EPICS can be related to by the rising number of archived PVs over time.

- Readback of magnet power supplies. The implementation of the function generators would push a set value to the magnet power supply, but no control of that was implemented. If there would be a fault condition of the function generator or the magnet power supply, the magnet would get a wrong current, noticed mostly in the loss of the stored beam. To find faults more easy, a readback system was implemented utilizing the magnet power supply control output.
- Control of pneumatic drives is done via a 24 V digital output
- Stepper motor control of Beckhoff stepper motors could be realized by an extension of the DIAMOND implementation provided by iThemba LABS. This was used controlling the position of the stripping foil used during injection, which as COSY is a charge changing injection.

Problems with the Beckhoff installation occurred with the internal switching of the EL3104 4 channel analog input. Because of the common ground there might crosstalk of the channels, which occurs especially when connecting devices with a different polarity to the the same device. This could be solved by replacing them with the isolated EL3174-0002 devices.

Beam Loss Monitor The initial beam loss monitoring system at COSY consisted of several scintillation detectors with an NIM based rate-meter readout. The disadvantage of the system was the not remote controllable power supplies, which lead to under-counting or signal saturation. As by the time the upgrade to EPICS was done there were commercially available multichannel power supply, featuring an internal EPICS control. We decided for a device from CAEN A.p.A. For the readout, to also have the system compatible with EPICS, we decided to self-develop a discriminator / counter and EPICS IOC on a Red Pitaya. This is a 2 channel ADC board featuring an Xilinx Zynq 7010 FPGA including a dual ARM Cortex A9+ processor. The details were presented in [9].

Tune Monitoring Described in details in [10], a new measurement tool for the betatron tune was determined. As a characteristic of the new system is the usage of bunch-by-bunch, provided by the during the upgrade process introduced Libera Hadron beam processors . It allows for a discrete tune measurement within a few milliseconds, as well as continuous tune monitoring during beam acceleration. The high precision tune measurement also enables determination of the beam chromaticity. The measurement is done while the betatron oscillations of the beam are excited with a band-limited RF signal via a stripline kicker and the subsequent tune change is determined. For routine use during beam operation and experiments, the developed method is integrated into the control system.

Injection Optimization using Machine Learning With the control and readback converted to EPICS access, an easy access to control of the beam optics of the injection beamline was possible. In order minimize the optimization time of the injection, which is crucial for the beam intensity within the synchrotron, reinforced learning optimization for the injection into the COSY synchrotron was developed, as described in details in [11].

LESSONS LEARNED

Giving the requirements of the upgrade, especially the requirement that the upgrade had to cause basically no downtimes of the synchrotron, the overall transition would have to be rated as an overall success. For the requirements of the COSY synchrotron, EPICS still seems like the best choice, therefore nothing would have been done differently if a new choice would be done today. With the availability of a lot

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of readay-to-use software, like Control System Studio, the EPICS Archiver or Save & Restore, with a low effort a huge upgrade could be realized.

With the step-wise approach one disadvantage surfaced: A lot of effort was spent to define and program the interface of an upgraded system towards one which was not yet upgraded. As some of these systems were upgraded in the following step, the whole interface development process was rendered obsolete in this following step.

In addition, the limits of the old systems oftentimes limited the overall performance of the whole system, like the function generators of the steerer magnet power supplies accepting a setting update only every 2 seconds. This caused the orbit correction being far from a state of the art system. As well, safety mechanisms had to be implemented, which were not implemented in the first place. In retrospective, upgrading more hardware devices, like the function generators in the first place would have been probably the faster and more elegant way, as as well the 20 years old hardware is showing more and more failures with limited supply of spare parts.

The company Cosylab, d. d., Control System Laboratory, was actively supporting the whole upgrade process. Cosylab and IKP were working together on the requirements, design documents, testing, and profiling the functionalities. It is important to describe existing machine features, find the possible means for introducing new functionalities, review, iterate and converge on the final design shape. For implementation and during the testing period, we found it invaluable to work together. Then, as issues arise, additional features are needed or the performance has to be improved. We achieve the latter by continuous and dynamic weekly work prioritization, planning and reporting.

OUTLOOK

The actual beam time plan foresees the end of user beam operation at COSY at the beginning of October 2023, while the injector cyclotron JULIC is still scheduled for further user operation, like for the High Brightnes Neutron Source (HBS) [12]. No immediate plans for further upgrades are on hand, but need might still arise during further beamtimes at JULIC. We appreciate the experience we cloud gather through the whole process and hope we can put it to use at other projects, like the already mentioned FAIR project of the GSI, Darmstadt or the HBS, where COSY might serve as testbed.

REFERENCES

[1] N. Bongers *et al.*, "Expertsystem for COSY - Control", in *Proc. EPAC'88*, Rome, Italy, Jun. 1988, pp. 1126–1129. https://jacow.org/e88/PDF/EPAC1988_1132.PDF

[2] R.J. Rausch, "Bus Systems For Process Control", *Europhys. News*, vol. 22, no. 2, pp. 40–42, 1991. doi:10.1051/epn/19912202040

[3] M. Rosenthal and A. Lehrach, "Spin Tracking Simulations Towards Electric Dipole Moment Measurements at COSY", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 3764–3766. doi:10.18429/JACoW-IPAC2015-THPF032

[4] K. Reimers *et al.*, "Upgrade of the Beam Profile Monitoring System in the Injection Beam Line of COSY", in *Proc. IBIC'15*, Melbourne, Australia, Sep. 2015, pp. 344–346. doi:10.18429/JACoW-IBIC2015-TUPB016

[5] I. Kohler *et al.*, "Progress in the conversion of the in-house developed control system to EPICS and related technologies at iThemba LABS", in *Proc. ICALEPCS'11*, Grenoble, France, paper MOPMS013, pp. 347–350. https://jacow.org/icalepcs2011/papers/MOPMS013.pdf

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

[7] U. Pedersen *et al.*, "Use of AreaDetector and EtherCat at Diamond beamlines", EPICS collaboration meeting 2012, https://epics.anl.gov/meetings/2012-10/program/1023-B4_Use_of_AreaDetector_and_EtherCat_at_Diamond_beamlines.pdf

[8] Murali Shankar *et al.*, "The EPICS Archiver Appliance", https://github.com/slacmshankar/epicsarchiverap

[9] I. Bekman *et al.*, "Experience and Prospects of Real-Time Signal Processing and Representation for the Beam Diagnostics at COSY", in *Proc. ICALEPCS2017*, Barcelona, Spain, Oct. 2017, paper TUPHA213, pp. 970–972. doi:10.18429/JACoW-ICALEPCS2017-TUPHA213

[10] P. Nidermayer *et al.*, "Development of a Fast Betatron Tune and Chromaticity Measurement System for COSY", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 983–985. doi:10.18429/JACoW-IPAC2021-MOPAB319

[11] A. Awal *et al.*, "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

[12] T. Brückel and T. Gutberlet (Eds.), "Conceptual Design Report Jülich High Brilliance Neutron Source (HBS)", ISBN 978-3-95806-501-7 (Volume 8), https://juser.fz-juelich.de/record/884799/files/Allgemeines_08.pdf