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ARCHITECTURE OF THE CONTROL SYSTEM FOR THE JÜLICH HIGH BRILLIANCE NEUTRON SOURCE

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Abstract

In the Jülich High Brilliance Neutron Source (HBS) project Forschungszentrum Jülich is developing a novel High Current Accelerator-driven Neutron Source (HiCANS) that is competitive to medium-flux fission-based research reactors or spallation neutron sources. The HBS will include a 70 MeV linear accelerator which delivers a pulsed proton beam with an average current of 100 mA to three target stations. At each target station the average power will be 100 kW generating neutrons for at least six neutron instruments. The concept for the controls system has been developed and published in the HBS technical design report. Main building blocks of the control system will be Control System Studio, EPCIS and Siemens PLC technology (for vacuum, motion, personnel protection...). The timing system will be based on commercially available components from Micro-Research Finland. The accelerator LLRF will rely on MTCA.4 developments of DESY that are commercially available, too. A small fraction of the control system has already been implemented for the new JULIC neutron platform, which is an HBS target station demonstrator that has been developed at the existing JULIC cyclotron at Forschungszentrum Jülich.

THE JÜLICH HIGH BRILLIANCE NEUTRON SOURCE PROJECT

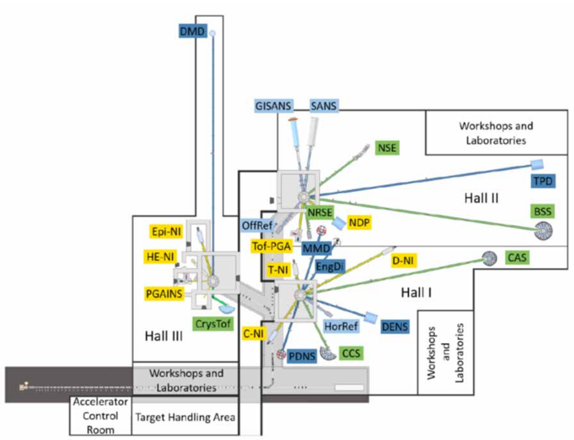

Figure 1: Layout of the planned HBS facility.

The Jülich HBS project [1] aims at the development of a novel High Current Accelerator-driven Neutron Source that fills the gap between neutron lab sources and high flux spallation sources. As shown in the planned layout in Fig. 1 it consists of an ion source, a LINAC and a multiplexer that distributes the pulsed proton beam via a high energy beam transport (HEBT) structure to three targets stations with more than 20 neutron instruments. The LINAC will provide 70 MeV protons at 100 mA peak current with different optimized pulse structures to each target station. Neutron production at the tantalum targets is based on a nuclear reaction, which yields a neutron flux at the neutron instruments similar to a medium flux research reactor, due to the optimized reflector/moderator setups very close to the targets.

HBS CONTROL SYSTEM ARCHITECTURE

The HBS control system consists of components and tools, which connect all HBS equipment and present a homogenous and ergonomic interface to operators, engineers and physicists enabling safe and reliable operation of the HBS.

From a control system point of view, the HBS can be subdivided into the HBS machine consisting of ion source, accelerator system (LINAC, HEBT…), target stations and conventional facilities (cooling water, pressed air,…) which is responsible for neutron production, and the instruments using these neutrons for research. For the HBS machine a central control room is foreseen that is permanently manned with operators, whereas instruments are locally controlled by dedicated measurement scripts and programs. Ideally there will be one integrated control system for the HBS machine in order to reduce the development efforts and support a homogeneous user interface. Since the ion source and the conventional facilities will be provided by external partners, it is quite likely that they will come with their own control systems. In order to reduce the overall costs, these control systems will not be replaced but extended by gateway functions to the integrated HBS control system.

Operation of neutron instruments is typically fully automatic, requiring presence of instrument users or scientists only for measurement definition and start, for development and test of dedicated scripts or for sample change. From the perspective of the control system, instruments and HBS machine are only loosely coupled via the timing system,

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personnel protection system, vacuum system and exchange of some information on the machine state (e.g. pulse charge and proton energy, …). Due to this loose coupling and the different mode of operation, it is foreseen to have individual control systems for each instrument, independent of the integrated control system of the HBS machine. Since requirements are different, the control systems of the HBS machine and the HBS instruments will use different control system technologies and implementation approaches. JCNS has been developing neutron instruments since decades and operates 12 instruments at its main outstation at the FRM-II in Garching. All these instruments share the same architecture and technologies for the instrument control systems, based on TANGO, NICOS and Siemens S7 PLC and motion technology. In order to minimize the implementation efforts by relying on the existing developments and the support of trained personnel, all HBS instrument control systems shall be implemented with the same architecture and the same technologies. Reusing the existing framework with out-of-the-box software components will lead to an extremely cost-efficient implementation of the instrument control systems. As a consequence, the following sections will concentrate on the HBS machine control system and the neutron instrument control systems will not be covered any more.

The HBS control system will be designed as distributed and object-oriented system following a classical three-tier architecture as indicated in Fig. 2.

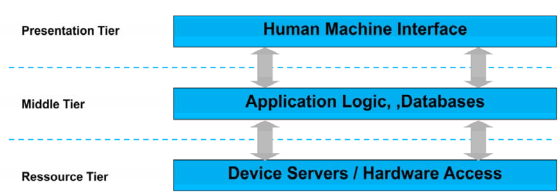

Figure 2: Three-tier architecture of the HBS control system.

At the lowest level, the **resource tier** facilitates the access to the front-end equipment of the HBS machine enabling direct equipment control and data collection. Conceptionally, the resource tier presents a device abstraction of front-end equipment to the middle tier. For the connection of the front-end equipment a wide range of interface standards has to be supported.

The **middle tier** implements the application logic of the control systems, e.g procedures for automatic start up, shutdown or auto-tuning. Databases for configuration, archived process variables (PVs) and logging information reside at this tier. A name service implemented at the middle tier provides location transparence for the devices exported by the resource tier.

The **presentation tier** is responsible for the HMI (Human Machine Interfaces) that enables machine and instrument operation for operators, engineers and physicists. At the presentation tier a variety of graphical and non-graphical tools are running on console computers which implement an abstract, aggregated and homogenous view of the HBS and hide unwanted details.

The HBS machine control system functions can be grouped horizontally according to the machine subsystems:

Ion source: The ion source will be provided by an external partner. If possible, the ion source control will be integrated into the accelerator control system. Otherwise, a gateway function to the ion source control system will be implemented

Accelerator: Core function is the RF system responsible for the definition, acceleration and guidance of the proton beam. Equipment to be controlled includes RF cavities and power supplies for magnets, using the beam instrumentation devices like beam position monitors or beam current monitors. Accelerator control can be further subdivided into control of LEBT, RFQ1, MEBT1, RFQ2, MEBT2, DTL and HEBT.

Beam dump: The control system is responsible for monitoring beam dump parameters like temperatures, radiation levels or beam current. Violations of configurable thresholds will lead to interlocks in the machine protection system and in the personnel protection system.

Target stations: Target station control can be further subdivided into target operation (monitoring, cooling), target exchange and cold moderator control. Main control functions are temperature control, vacuum control, cooling, gas management, personnel safety and target handling. Equipment to be monitored and controlled includes motors, pumps, valves, leak detectors, pressure gauges and temperature sensors.

Vacuum system: There will be a common vacuum system for the ion source, the accelerator, the target and the neutron guides. In the vacuum subsystem different types of pumps in differential pumping systems, valves and pressure gauges have to be controlled and monitored.

Conventional facilities: This subsystem is responsible for the control of pressed air, water and electrical power supply, including the control of compressors, pumps and valves as well as the continuous monitoring of process values like air pressure, air flow, water pressure, water flow, water temperature and electrical power, voltage, current, cos phi of all main circuits. It is expected that the conventional facilities will be delivered by commercial companies together with their corresponding control functions. In this case, gateways to the integrated HBS control system have to be implemented.

Orthogonally to this horizontal structure, the HBS control system structured into the following functional groups which are related to all subsystems:

HMI: On operator consoles and wall displays in the control room GUIs will be implemented that allow control, optimization and state supervision of the HBS machine. This includes presentation of real-time summaries of all relevant machine parameters. For standard operation, easy startup, shutdown and auto-tuning buttons will be offered. The role-based access allows the presentation of different granularity levels to individual user groups. Homogeneous appearance and a good ergonomic behaviour are key design goals for all GUIs.

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Alarm/Logging System: The alarm and logging system is responsible for the collection, distribution and archiving of alarms (information on abnormal situations) and the logging of events (diagnostic information). At the presentation tier, a GUI-based console application allows the definition of alarms and logging events, presents these to the operator and supports the retrieval of archived alarms and logged events.

Process Archive: During the operation the HBS machine all relevant process data have to be collected and archived for later analysis. A graphical tool allows selection of process data for archiving, definition of archiving intervals and persistence times in the archive. A data browser serves as a graphical front-end for later retrieval and presentation in configurable graphs, e.g. as time series.

Electronic Logbook: The electronic logbook is a software tool that is used for the communication between the accelerator personnel. It allows adding observations and comments during accelerator operation and combining these with accelerator state information and measurement data. It is integrated into the control system and typically has a client server architecture using a database.

Timing system: Due to the pulse structure of the proton beam, neutron instruments and HBS machine components have to be synchronized. This can be achieved with a central clock that is distributed via a dedicated timing network together with event, trigger and state information. Timing receivers have to be implemented at individual devices that decode timing and event/trigger/state data and generate pulses and clocks for the synchronization of the device hardware.

LLRF (Low Level Radio Frequency) system: Central functionality of the LLRF system is the control and stabilization of the RF field of the cavities by implementing complex filters and feedback loops. Additionally, the LLRF is responsible for the cavity tuning via stepper motors.

Beam diagnostics: During accelerator operation beam parameters have to be monitored. This is accomplished with a variety of diagnostic devices like beam position monitors, beam current monitors or beam loss monitors. Selection of diagnostic devices should consider the availability of commercial readout electronics. The control system will provide access to the beam parameters by interfacing the readout electronics.

Machine protection system (MPS): The Machine Protection System has to avoid machine damage or unwanted radiation due to device failures or abnormal events like beam loss, failure of a cooling system or failure of the vacuum system. It will be designed as a failsafe system shutting down targets stations, accelerator or ion source in the case of a fault. It will have a distributed architecture consisting of input devices, output devices and a beam interlock system, connected by a dedicated optical MPS network. The beam interlock system will be based on FPGA technology to ensure fast reaction times. Due to the independent operation of the target stations in in the states IDLE, COMMISSONING and BEAM-ON, shutdown interlocks as well as the HBS components affected by a shutdown must be dynamically changed according to the state of the targets.

Personal protection System (PPS): The personal protection system has to ensure the protection of humans against any hazards from the machine, which may lead to injuries. Main focus is the exposure to radiation, but also other hazards like electrical shock have to be prevented. The personal protection system will be implemented as a highly reliable failsafe system that ensures a safety level according to ISO 13849 PL e (roughly corresponding to IEC 61508 SIL 3). With regard to radiation safety it will manage entrance and exit from radiation-controlled areas. Additionally, radiation levels will be monitored. Any access violation or any violation of radiation level thresholds will lead to immediate shutdown of ion source and accelerator.

Operational Security: Since remote network access to the HBS machine control system shall be allowed, appropriate cyber security mechanisms have to be implemented. One of the mechanisms is the strict separation between the technical network with the control devices from the standard office network. In order to reduce operational faults, a role-based access to the control systems has to be implemented that gives different levels of control to specific user groups.

Automation and State Transitions: The control system will provide a scripting interface that allows the definition of high-level procedures for automatic execution of complex sequences of tasks. One dedicated high-level procedure will be a Master Control Task, that will execute state transitions of the accelerator. At least the following states will be defined: Normal Operation (Beam On), Commissioning, Maintenance, Idle and Fault. The control system will provide mechanisms to record and play back control system configurations and operational sequences.

HBS CONTROL SYSTEM TECHNOLOGIES

For a cost-effective implementation of the HBS it is intended to reduce the overall development effort of the HBS control system as much as possible, leading to the following requirements:

- Only technologies shall be used that are well established in the international accelerator community.
- Commercially available systems and components shall be used as much as possible and the number of different vendors and standards should be minimized.
- The existing expertise of the personnel of Forschungszentrum Jülich shall be used as much as possible.
- Cooperation with scientific partners shall be sought for the implementation of subsystems, e.g. the machine protection system or the LLRF system, with the goal of sharing as much as possible from existing systems at the partner labs. Potential partners are ESS, PSI, MYHRRA and DESY.

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With these requirements, the following central decisions regarding selection of control system technologies have been made.

Software framework for the control system core: Since EPICS is most commonly used in the physics accelerator community and since it is open source software supported by a large community, it has been decided to use EPICS as the software framework for the accelerator control system core. This decision is further supported by already existing EPICS expertise in Forschungszentrum Jülich and the fact that it is used at potential partner facilities like Myrrha, ESS, ISIS or PSI. From the architecture point of view, EPICS is designed as a distributed client server system where so-called IOCs (Input Output controllers) exchange process data in form of process variables (PVs) with client computer systems via the Channel Access protocol. The Channel Access Protocol is based on Ethernet and UDP or TCP. EPCICS V7 introduced a new protocol called PVaccess that allows the access to structured and distributed data. Central functionalities of EPICS are location independence and device abstraction using device server software on IOCs which provide a common interface independent of a specific hardware device. The IOCs are computer systems to which all front-end electronics are connected. Historically, IOCs were implemented as VME systems with the commercial real time operating system VxWorks. Today it is possible to use PCs with Linux or the open source real time system RTEMS as IOCs. IOCs in the HBS accelerator control system shall be based on industrial PCs with Linux, normally. RTEMS shall only be used only when real time operation is required.

Software framework for HMIs: Historically, a variety of different HMI tools and applications have been developed in the EPICS context. Today, most recent EPICS projects use Control System Studio (CSS) as a software framework for HMIs. Originally started around 2006 as a joint effort of DESY and SNS, CSS now is open source software which is used by a broad community (APS, BNL, ITER, DIAMOND, ESS…). It is a very large system consisting of about 2 Million lines of Java source code. Due to the common use and the extensive functionality of CSS, it has been decided that it shall be used as HMI software framework for the HBS accelerator control system.

CSS consists of a synoptic editor for development of new HMI tools and a collection of ready-to-use tools which cover most HMI requirements of an accelerator control system, like alarm system, process archiving system or electronic logbook. It is based on Eclipse RCP and a version independent of Eclipse, called Phoebus, is available, too. CSS supports Oracle, MySQL or PostgreSQL as relational databases for the storage of PVs, alarms or log messages and it has not yet been decided which of these databases will be used for the HBS control system.

CSS is a highly modular system based on plugins. It can easily be extended by new software components and existing software components can easily be exchanged by new ones, simply by providing a wrapper around the new software component that conforms to the plug-in interface. The consistent design of CSS provides a homogenous and ergonomic interface to the user. E.g. it is easy to select a PV in the context menu of one CSS tool and send it to another CSS tool.

Computer and network technologies: Server computers as well as front end computer systems will be based on PC technology using Linux as operating system. Front end computer systems – e.g. IOCs - will be industrial PCs. The formfactor will depend on the requirements. E.g. for the LLRF system MicroTCA systems will be used, which is heavily deployed at many recent accelerator control systems, like XFEL or ESS. In other scenarios PXIe or CompactPCI Serial seem to be good choices. Also, virtualization is an option for IOCs, when front-end equipment is connected via TCP/IP or UDP.

There will be dedicated communication systems for the timing system and for the machine protection systems. For PLC type of equipment fieldbus systems like Profinet or IO-Link will be used. Otherwise communication will be based on Ethernet, using TCP/IP or UDP.

PLC technologies: The front-ends of the cooling subsystems, of the conventional facility subsystem and of the vacuum subsystem will follow a distributed architecture implemented with industrial grade PLCs and decentral periphery systems connected via field bus systems. Due to the long-term experience of JCNS and the market dominance, it is intended to use Siemens S7-1500 as PLC systems, ET200SP and ET200MP as decentral periphery systems and PROFINET, PROFIBUS, AS-i and IO-Link as fieldbus systems. At the HBS control systems resource tier, industrial PCs are used that are connected via PROFINET to these front-ends. The implementation of the personal protection system will be based on the Siemens distributed safety concept with failsafe S7-1500F CPUs, failsafe F-Modules and PROFIsafe communication, which allows to achieve PL e according to ISO 13849.

Timing system: An interesting candidate for the timing system is White Rabbit developed by CERN as an improvement of the Precision Time Protocol (PTP) according to IEEE 1588, achieving sub-nanosecond accuracy. Unfortunately, White Rabbit only defines clock synchronization and the timing network. Higher level services like trigger distribution and event protocol have to be defined and implemented specifically for each facility. The commercial support for White Rabbit is limited, too. Therefore, it has been decided to use the timing system available from the Finnish company Micro-Research Finland (MRF) for the HBS accelerator control system, also because MRF is widely used in the accelerator community and employed by the potential HBS cooperation partners ESS and PSI, too. The MRF timing system defines already an event/trigger distribution protocol and the timing system generator is equipped with a programmable sequencer for triggers and events. Free FPGA code implementing the event receiver is available, e.g. for the integration into detector electronics.

A wide range of event generator, switch/fan-out and event receiver modules for different formfactors - including MicroTCA.4, VME, CompactPCI, PMC and PCIe – are commercially available from MRF and well-supported by

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EPICS. For the HBS accelerator control system MicroTCA.4 is the preferred choice, which allow the easy integration into the LLRF electronics that is based on MicroTCA.4, too.

LLRF: Commercial modules are available on the market for the LLRF implementation. It is intended to use SIS (Struck Innovative Systeme) MTCA.4 modules 8300-KU and DWC8VM1 for the HBS LLRF. The 8300-KU is an ADC module that will be used as a FPGA processor for the implementation of IQ demodulation, PI feedback controller and a network of filters, in similar way as the ESS LLRF implementation. The DWC8VM1 is a vector modulator originally developed by DESY that will be used for the IQ modulation.

HBS TARGET STATION PROTOTYPE AT THE NEW JULIC NEUTRON PLATFORM

A target station prototype for the HBS was built at the COSY facility at Forschungszentrum Jülich in order to demonstrate the feasibility of the concepts and to test essential components like target, reflector/thermal-moderator setup and the cold moderators [2]. JULIC, the injector cyclotron for cooler synchrotron COSY, is also used as a proton source for the target station demonstrator providing 45 MeV proton pulses at 25 Hz repetition rate and 8 µA peak current. The target setup includes two neutron instruments, the reflectometer HERMES provided by LLB and the diffractometer TOAD. A liquid hydrogen cold moderator has been built that is used by HERMES and a solid methane cold moderator has been built that is used by TOAD. Several successful beam times have been provided at this so-called JULIC Neutron Platform since December 2022, during which additional neutron extraction channels have also been used by external groups. Fig. 3 shows the JULIC Neutron Platform, with the blue target shielding in the centre, the proton beamline in the front and the neutron instruments TOAD and HERMES at the right side.

Figure 3: JULIC Neutron Platform.

A control system has been built for the target station, that consists of the following subsystems:

- **Target cooling system**, which provides the water cooling for the target.
- **Target vacuum system**, which is responsible for the vacuum in the tube structure, that surrounds the target.
- **Target handler system**, which controls a complex mechanical device for the insertion and extraction of target and target plug from the target shielding.
- **Target shielding gate**, which is responsible to open the target shielding via an electro-cylinder driven by a servo motor.
- **Personal protection system**.
- **Liquid hydrogen moderator control** and **solid methane moderator control**.

The implementation of all these subsystems heavily relies on Siemens PLC technology. Due to the short development time of less than two years, it was decided, not to use EPICS and CSS as the software framework for these subsystems. Instead NICOS and TANGO have been used, taking advantage of existing software solutions and trained personnel. This reflects also the fact that the JULIC neutron platform is not a fixed installation that is operated in a static way by an operator team, but a dynamically changing experimental setup, where NICOS is much more appropriate, due to its strong scripting capabilities. A later transition to CSS and EPICS will be possible without any hardware changes.

Due to the supply chain disturbances caused by the coronavirus pandemic, not all required equipment could be acquired in time. By improvisation employing existing spare parts, all control system functions have been implemented to the extent necessary to operate the target station demonstrator. Especially the personnel protection system is only partially implemented and will be completed until the end of 2023.

CONCLUSION AND OUTLOOK

Forschungszentrum Jülich has started the HBS project for the development of a novel High Current Accelerator-driven Neutron Source. A detailed technical description of the HBS is published in a technical design report and a prototype for an HBS target station has been built using protons from the cyclotron JULIC. The HBS control architecture and its central technological building blocks have been discussed in this paper. A fraction of the HBS control system has already been developed for the target station prototype. In a next step it is intended to build the ion source and the first section of the Linac that should provide a considerably higher proton current to the target station than the JULIC cyclotron.

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