THE MEDAUSTRON ACCELERATOR CONTROL SYSTEM: DESIGN, INSTALLATION AND COMMISSIONING

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Abstract

MedAustron is a light-ion accelerator cancer treatment facility built on the green field in Austria. The accelerator and its control systems have been developed under the guidance of CERN within the MedAustron – CERN collaboration. Civil engineering was completed in October 2012 and accelerator installation has started in December 2012. Accelerator control deployment started in January 2013. This contribution gives an overview of the accelerator control system project. It reports on the status of commissioning including ion sources, low-energy beam transfer and injector. The major challenges so far have been the readiness of the externally supplied IT infrastructure and the need to commission the control system before installation of frontend devices. The control system has been released for accelerator commissioning within time and budget.

ACCELERATOR OVERVIEW

The heart of the facility is a synchrotron, designed and developed under the guidance of CERN, aiming at very stable beam intensity to deliver prescribed dose using quasi-continuous spot scanning with variable energy ranges from 60 to 800 MeV/u for protons, carbon and future ion beams. The machine has been designed in the scope of the Proton Ion Medical Machine Study (PIMMS) at CERN from 1996 to 1999 [1]. The facility has been built on the green field in Wiener Neustadt, Austria in less than 1.5 years. From inception to completion, including setting up the development environment, production of hardware and software, procurement and building up an engineering team at CERN, five years have passed. Accelerator infrastructure installation has started in late autumn 2012. One ion source was commissioned by March 2013, the first power converters were released for remote operation in May 2013. At this time testing of the full scale accelerator control system could start. As installation continues, accelerator partitions are commissioned with the operational control system, Fig. 1.

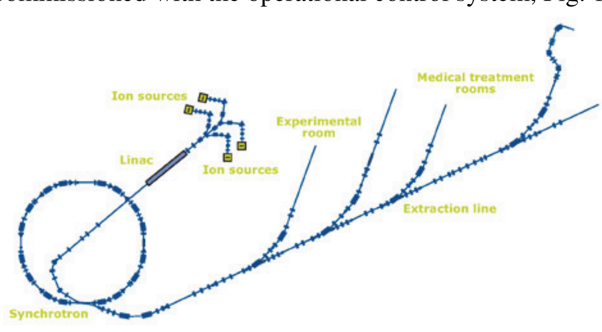

Figure 1: Layout of the MedAustron accelerator.

ACCELERATOR CONTROL SYSTEM

The accelerator control system has been architected and designed at CERN [2], partially integrating lessons learned from the CNAO project [3], CERN accelerators as well as adapting design patterns and technologies developed for the CMS experiment [4]. The system controls ~250 power converters for ~300 magnets, 3 ECR ion sources each one consisting of about 30 devices, 561 vacuum devices (valves, pumps and gauges), 5 beam stoppers, 4 injector RF amplifiers and 1 low-level RF system, 1 distributed set of 12 synchrotron RF amplifiers and 1 synchrotron low-level RF system and ~100 beam diagnostics devices.

All static definition of beamline elements and controls devices, characteristics of magnets, dynamically calculated front-end device settings, software, network and application configuration and definition of logical partitions are managed using a repository management system (RMS) database application, which is an evolution of the CNAO RMS. Accelerator operation is based on cycle-to-cycle modulation, each cycle corresponding to a defined set of beam characteristics shown in Table 1.

Table 1: Beam Characteristics for a Cycle

Characteristic	Description
Ion	p, C etc. up to 7 species in total
Energy	0 - 900 MeV in steps of 0.1 MeV
Dimension	1 to 10 mm in x and y independently
Intensity	100%, 50%, 20%, 10%
Spill	16 defined spill durations from 0.1 to 120 sec including open ended
Source	Up to 7 sources branches supported
Beamline	Up to 15 target irradiation rooms and intermediate beam dumps supported
Rotator/Gantry	0-210 mapped to a gantry angle

Device settings for several thousands of different cycles are programmatically generated using a cycle-builder application. It relies on element geometry information, MAD-X properties of beamline elements, front-end device information and an XML accelerator model. Calculation is fast, taking several seconds for thousands of cycles. Import to and export from RMS taking about three hours each is currently the dominating factor when creating new configuration baselines. Settings and software are stored on a Web server from which frontend controllers (FEC) autonomously pick the data. Switching between configurations, including restart of all FECs and downloading all data takes less than 10 minutes.

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For operation, a sequence of cycles is put into a run file that is provided to the control system when the machine is allocated. The machine can be partitioned into virtual accelerators (VAcc) that are made up from contiguous sets of beamline elements and their FECs. An operator in front of the screen or a program such as a commissioning procedure or a treatment control system can allocate any defined VAcc via the virtual accelerator allocator (VAA) software component. A VAcc is allocated in one of four modes. For medical operation, a subset of cycles and settings are permitted and configurability of FECs is limited. In machine physics mode the operator can freely modify cycle-dependent settings that will be used for the immediate next cycle. The VAA manages priorities, user allocation, consistency checks, distribution of a run file, safety preserving actions such as beam stopper operation, power converter standby/on switching, state changes and monitoring of VAccs. Once allocation has completed, clients request beam cycles via the main timing system (MTS). Up to five timing sequence execution slots can run in parallel, letting operators generate beam, commission hardware or develop software concurrently. While one beam cycle is generated, the next beam cycle can already be requested. The frontend controllers re-configure for the next beam cycle, while beam generation is still ongoing. Re-configuration time are shorter than 250 msec, avoiding dead-times between beam cycles.

DEVELOPMENT PROCESS

The accelerator control system project was set up by defining a development process that follows the Enterprise Unified Process and the V-model software lifecycle (see Figure 2) from the EN 61508 functional safety and the EN 62304 Medical Device Software Life Cycle Processes standards. A configuration management infrastructure following ISO 10007 was adapted from the development of the Compact Muon Solenoid experiment's data acquisition system. Considering the need to deliver in less than four years and to develop concurrently to design and production of the accelerator elements, we opted for the following strategy:

Technical management at CERN led the project, formulated requirements, concepts and designs based on existing systems and expert knowledge, implemented the development process and ensured compliance. A team was built up at CERN to develop application software, integrate and test fully functional control system columns spanning all components from user interface to the equipment under control. A contractor with experience in the field of accelerator control systems developed real-time control components according to the established development process. Requirements were refined as a cooperative effort with the contractor, design and implementation was carried out by the contractor and was reviewed by the core team. Regular integration weeks at CERN at distances of 8 weeks served verifying that requirements were commonly understood, implemented functions behaved as expected, mishaps were identified and corrective actions were commonly elaborated. Running-away activities could be discovered and re-prioritization of tasks was possible. The project covered 85 person years over a time period of four years.Two persons at CERN were in charge of architecture and project management, 8 persons formed the in-house core development and integration team, half an FTE was required from CNAO (Italy) for RMS and technical consultancy, 4 to 15 FTEs with varying involvements from Cosylab (Ljubljana, Slovenia) were active throughout the development period.

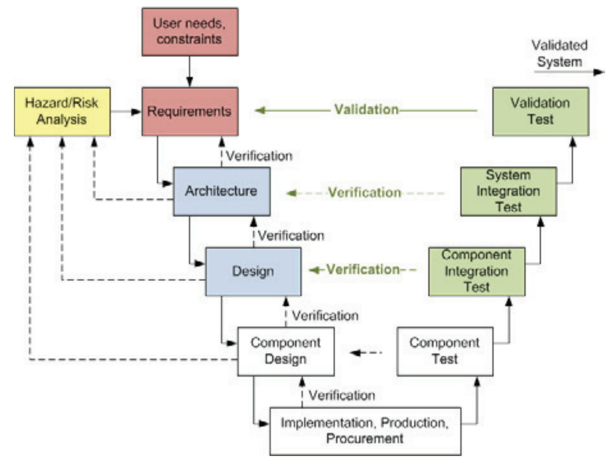

Figure 2: V-model applied for systems engineering process as taken from EN 61508 and EN 62304.

DESIGN

The **control system follows a four-tier architecture model** as described in [5]. The individual components in each tier are depicted in Figure 3. The **presentation tier (1)** includes mainly user interfaces. Panels are created using WinCC OA for which a browser-like navigator framework following EN 60601-1 medical device and US FAA guidelines has been developed. Contents are visualized using the natively supported features, with in-house developed Qt widgets for online and 3D visualization and with integrated Labview panels. Accelerator commissioning procedures are written in C# with WPF UIs. A log viewer and a RMS data inspection interface are also written in C#.

The **processing tier (2)** hosts the Oracle 11g based accelerator configuration settings repository, the SIEMENS/ETM WinCC OA 3.9 SCADA system with representations of physical devices, implemented as state-machine scripts and applications to generate cycle settings from the machine model. Transition to WinCC OA 3.11 is scheduled for a commissioning pause period. A logging server concentrates, archives and relays log messages from all components at all tiers over the network. Build and deployment systems ensure consistent management of software and configuration data that are made available on a Web server. WinCC OA integrates with the building's Safety Management System to provide the accelerator status and to obtain environmental conditions to determine if the accelerator can be operated. Integration with a facility-wide role-based authentication

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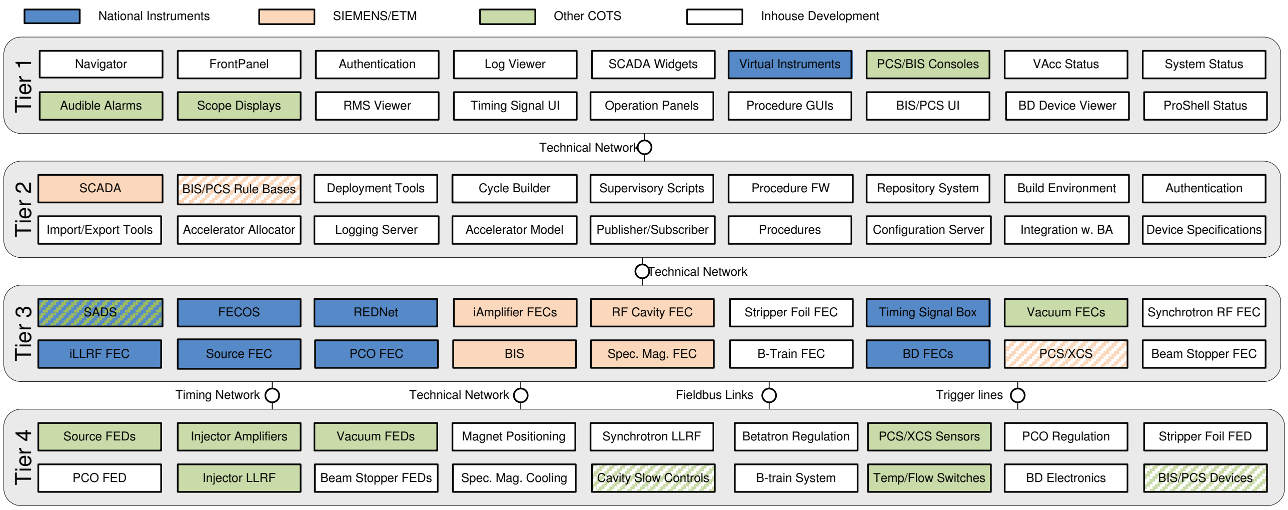

Figure 3: Accelerator control system components at four individual tiers.

system has been designed in WinCC OA using CERNs JCOP components.

The **equipment tier (3)** comprises the main timing system, FECs that directly control beamline elements or that integrate entire third-party systems at tier-4. The majority of FECs are NI systems, 3U PXIe-1082 8-slot crate, PXIe-8135 CPU, running Windows 7 64bit, programmed as Labview and Labview/FGPA applications under a light-weight frontend controller framework (FECOS). One front-end controller is a VME/VXS system, running SLC6 32bit (to be upgraded to 64 bit with latest WinCC OA version) on a MEN A20 CPU, 9U ELMA VXS subrack with 16 slots dual star topology. This system for the new CERN PSB low-level RF system is programmed in C++, directly linking the WinCC OA API Manager libraries to integrate in plug & play fashion into the WinCC OA based accelerator control system backbone. Few frontend systems, which are integrated via SIEMENS S7-400 CPU 417-4H PLCs have their FECs modelled as WinCC OA Ctrl scripts. Logically they are located at tier-3, but the software component resides in WinCC OA at tier-2.

An analogue Signal Acquisition and Distribution System (SADS) built from an NI PXIe system, a network of Pickering analogue switching matrices, multiplexers and three Tektronix M-series oscilloscopes permits engineers to perform sanity checks on equipment and analyse raw signals in a comfortable way via the control system graphical user-interface, thus avoiding cumbersome re-cabling activities and time-consuming dispatching of persons across buildings and floors.

The **front-end tier (4)** includes all devices and systems that control the beamline elements. Responsibility for these components is with the individual accelerator work packages. They are integrated via FECs at tier-3.

DEPLOYMENT

All IT and the majority of accelerator control system components are located in a data center above the synchrotron hall to ease system management. There exist five physically distinct networks: (1) technical for particle accelerator, (2) general purpose for office use, (3) facility management for plant systems, (4) medical for clinical systems and (5) WLAN with various access levels for visitors, public access for employees and hospital/medical certified WLAN telephony for all employees. All systems except FECs and the Active Directory service run on virtualized Windows 2008 R2 or Windows 7 64bit. A Virtual Desktop Infrastructure (VDI) with Windows 7 based on Citrix serves end-user connectivity. A development environment for 20 persons is virtualized using one IBM x3850 system with 40 CPUs, 400 GB RAM and 5 TB local storage running VMWare ESX 5.0. Firewall and anti-malware appliances ensure that selected traffic can pass from one network to the other for isolated use cases. External access is additionally protected using an SMS passcode challenge system.

603 OM3 and OM1 optical fiber pairs with lengths between 20 and 150 meters for a total 52.8 km have been laid to connect the timing system (MTS) to front-ends, the power converter controllers (PCC) to power converters.

The deployed system consists of 1 MTS generator, 9 PCCs, 1 injector LLRF FEC, 1 synchrotron LLRF FEC, 1 SADS and about 15 beam diagnostics FECs. 3 PXI systems are embedded in the ion source enclosures. 1 PLC controls extraction septum position and implements safety logic for that device. Vacuum equipment is integrated using 10 Moxa NPort 5650 16-port terminal servers, 8 Moxa ioLogic E1210 16 DI and 6 ioLogic E1211 16DO networked IO modules, 1 SIEMENS S7-300 CPU 315-2 PN/DP PLC for sector valve control. 1 S7-400 CPU 417-4H implements the synchrotron RF slow controls. Two 417-4H PLCs with distributed ET 200M and ET 200L redundant Profibus periphery implement a beam interlock and radiation patrol system.

Control room fat-clients are 8 Lenovo TS130 with 4 screens each. Each workplace features 2 machines. Offices are equipped with Liscon 1135 thin clients with 2 screens providing access to the Citrix-based VDI in the public network. Connection to development virtual

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machines in the technical network is done via RDP that is enabled on a person-by-person basis. During commissioning, the technical network has one VLAN. For operation, one VLAN will be dedicated to production machines, one is used for the development environment and one will be reserved for treatment-related tasks.

INSTALLATION & COMMISSIONING

Installation of the control system started after availability of basic networking and IT infrastructure in November 2013. Remote access to a stable VDI and VM infrastructure was crucial, since the entire team was at CERN. A software development environment was set up at the facility site that was used remotely from CERN to build and deploy software. The primary development environment at CERN is maintained until the end of 2013. One ion source was commissioned in the first two months of 2013 with the control system. Beam commissioning using beam spectrum and emittance measurement procedures followed in March and April. Hardware commissioning of power converters started in May. Preparation of a control system site integration test followed in June. The summer period was used to commission power converters and to perform synchronization tests of power converters with the injector RF system for pulsed Linac operation. The injector chain is now operational and commissioning with a pulsed 1mA beam is ongoing. The synchrotron RF system will be delivered by the end of 2013. This milestone marks the decommissioning of the CERN based control system development environment.

LESSONS LEARNT

It was challenging to roll out a ready-to-use accelerator control system for a medical-grade particle accelerator before element design completion and availability of devices under control. A tight time-to-completion schedule made us seek assistance for implementation outside CERN, leveraging the resources of an experienced contractor. Our decision to mitigate project management risks by sharing responsibility was confirmed: the CERN team was in charge of fleshing out the requirements formally, reviewing designs and integrating contractor deliverables. In-house works included the definition of interfaces between tier-3 and tier-4, the definition and management of accelerator configuration data, the development of supervisory control and user interfaces, thus maintaining at all times an overall picture of the project. Regular integration weeks at CERN were an indispensable means to keep the project on track, in terms of functional scope, schedule and cost. Finally, an independent, external code reviewer has been engaged to verify quality and to help ensuring that improvements are independently reviewed. We conclude that there is neither a budget nor a quality reason to work with a contractor rather than taking an in-house development approach when it comes to build a system from scratch. The benefit of working with a contractor, however, is the possibility to be able to tap a large pool of qualified people quickly with the reassurance to deliver in time at predictable cost. This flexibility permitted us to raise and lower workforce according to project phase needs. The approach forced us to perform continuous housekeeping of our resources, requirements and constraints and to take pragmatic decisions, since the contractor would produce cost and schedule impact assessments before work would start. Our decision to define a series of contract work orders with lump sums for well-scoped deliverables was confirmed to be preferable over an all-in-one development package or compensation of efforts based on hourly rates. For our project, a chunk covered work that was manageable in four months. Smaller chunks would create too much administration overhead and larger ones would lead to a loss of control. In that way, an agile approach to track programmed versus earned value was possible with existing, Web based tools at CERN.

We experienced the benefits of controls engineers working closely with accelerator subsystem teams on requirements, design and review of software done by subsystem groups. Where this scheme was lived, interfaces stabilized early and completion of the work was possible within predicted time and cost margins. Where it was not possible to work in that way, software would have to be re-developed or integration had to be done with restrictions, leading to limited configuration and operation flexibility during the commissioning period.

CONCLUSIONS

A blueprint for a Medical Accelerator Control System (MACS) has been developed by CERN. It has been implemented in the scope of the MedAustron project under the guidance of CERN from March 2010 to March 2013. The system has been installed before the arrival of the first beamline elements such that hardware commissioning could start according to the master schedule. All functionalities required to operate the particle accelerator have successfully been demonstrated on-site. Software stability improvements are currently the contractor's main task. Ion sources, LEBT and Linac are beam commissioned with the operational control system. This marks the successful completion of large-scale knowledge transfer from CERN to a member state and from fundamental research to application.

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