ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUPHA064

THE LIGHT CONTROL AND INTERLOCK SYSTEMS

R. Moser, H. Pavetits, ADAM S.A., Geneva, Switzerland

Abstract

LIGHT (Linac Image Guided Hadron Technology) is a particle therapy system[1] developed by Advanced Oncotherapy plc. Accelerator, control and interlock systems are developed by its subsidiary A.D.A.M. SA, a CERN spin-off. The system is being designed to accelerate protons up to 230 MeV using a modular and compact 25-meter-long linear accelerator. It is being designed to operate in pulsed mode where beam properties (energy, pulse charge and spot size) can be changed at 200 Hz.

The LIGHT product will be installed in different facilities. As such, the installations will differ in accelerator and beam transfer line layouts, number of treatment rooms (with an optional gantry), facility services, equipment suppliers and equipment versions. Thus, the control and interlock systems need to be extensible through configuration and modularization. To achieve this, the control system relies on a multi-tier architecture with a clear separation between front-end devices and controllers. To minimize time-to-market, the systems rely mostly on COTS hardware and software, including a timing and triggering system and a light-weight software framework to standardize front-end controllers.

INTRODUCTION

ADAM S.A. is a CERN spin-off founded in 2007 in Geneva (Switzerland) developing applications of detectors and accelerators to medicine and is a subsidiary of London-based Advanced Oncotherapy PLC. ADAM S.A. is developing the linear accelerator to be used in the Linac for Image Guided Hadron Therapy (LIGHT) project of Advanced Oncotherapy PLC [1].

Current proton therapy solutions mostly rely on synchrotron and synchrocyclotron accelerators for accelerating protons. Driven by the recent advancements in linear accelerator technology, ADAM S.A. has designed a new linear proton accelerator as depicted in Figure 1. The main advantages are:

- **Precision:** the system has an active longitudinal modulation along the axis of beam propagation (beam energy and therefore the treatment depth can be electronically varied during therapy), rather than using a passive modulation system (where the cyclotrons' fixed initial energy is degraded by the interposition of variable thickness energy absorbers between the accelerator and the patient, causing a quality loss of the beam). Moreover, the LIGHT system has a dynamic transverse modulation that allows a precise 3D treatment of the tumours (spot scanning).
- **Compact:** the linear accelerator has compact dimensions compared to a cyclotron or synchrotron, therefore reducing size and costs of production and installation.
- **Modularity:** LIGHT is conceived as an assembly of modular units thereby facilitating installation and possible displacement to a different site. This specific feature offers radiation therapy centres complete freedom of customisation, allowing the choice of a wide range of maximum treatment energies.
- **High frequency:** the very short pulses (a few microseconds) typically for the linear accelerator and the high repetition frequency (up to 200 Hz) are extremely useful to perform a highly conformational therapy based on a fast 3D spot scanning of the tumour.

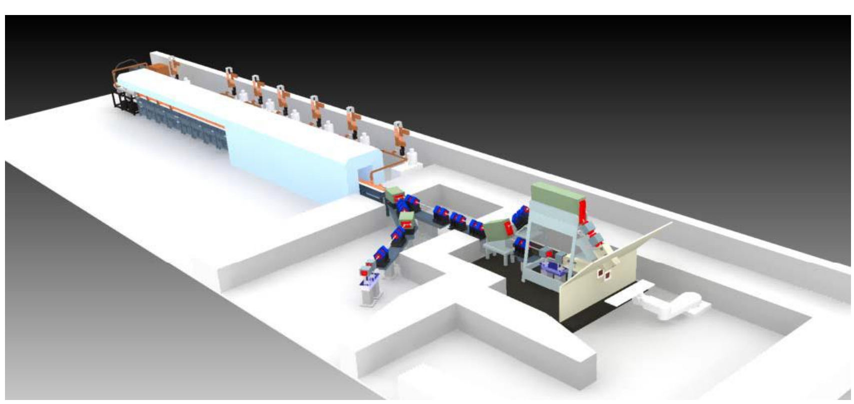

Figure 1: Example layout for LIGHT.

[1] The LIGHT Proton Therapy System is still subject to conformity assessment by AVO's Notified Body as well as clearance by the USA-FDA.

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Proton therapy is a kind of particle therapy where protons are used to irradiate diseased tissue. Beams of protons are accelerated in particle accelerators to a required energy before they are focussed into the cancerous tissue. The main advantage is that radiation is primarily deposited in the diseased tissue, exerting minimal damage to the surrounding tissue. Figure 2 shows the energy absorption as a function of depth for proton therapy as compared to conventional radiotherapy. The penetration depth of the protons is set by adjusting their energy.

LIGHT consists of a newly designed mechanical structure that offers a higher gradient of acceleration, which allows the protons to reach the maximum energy of 230 MeV within 24 metres. Due to its modular design, partial installation with a reduced maximum beam energy is also feasible for smaller buildings. The energy can be modulated by switching on or off one or more accelerating structures at the end of the accelerator. In addition, the last operating structure can fine-tune the final beam energy, which results in a precise hit. Energy switching can be done at 200 Hz. After each change the proton source emits a pulse containing 10^6 to 10^9 protons into the accelerator, depending on the required irradiation dose.

LIGHT CONTROL SYSTEM

The proton therapy system requires a control system for all accelerator and beamlines equipment and auxiliary systems. The main requirements include:

- **Repetition rate:** provide beam pulses with properties such as energy and dose that may change at a rate of 200Hz.
- **Modularity:** handling multiple suppliers for the same equipment type transparently in the control system with minimal impact on neighbouring systems.
- **Commercial off-the Shelf:** consider commercial off-the-shelf equipment where feasible to reduce time to market with suppliers providing long-term support required for the product.
- **Custom Suppliers:** Custom suppliers for the equipment in the frontend tier necessitates control system hardware vendors that are able to provide equipment with a variety of low-level interfaces.
- **Configuration:** management of configuration and calibration data.
- **Procedures:** automation of commissioning and quality assurance procedures for machine commissioning and operation.

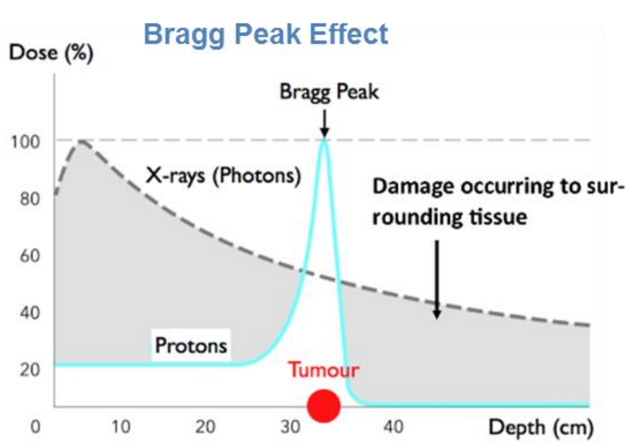

Figure 2: Energy absorption as a function of depth.

Architecture

The LIGHT Control System (LCS) controls the accelerator and beam transfer-line devices to generate and steer the beam into the correct treatment room. It relies on a standard multi-tier architecture, similar to other medical accelerator facilities [2][3] as outlined in Figure 3:

- **Presentation Tier** (Tier-1) provides user interfaces to control and monitor services in tier-2 and equipment in tier-3.
- **Processing Tier** (Tier-2) is responsible to configure and monitor the equipment in tier-3 and allows the user interfaces from the presentation tier to control equipment in a uniform manner.
- **Equipment Tier** (Tier-3) abstracts accelerator hardware specific interfaces into a uniform interface to the processing tier.
- **Frontend Tier** (Tier-4) contains the local control system with custom interfaces that control the actual accelerator and beamline hardware.

Accelerator Control System

The Accelerator Control System (ACS) consists of several front-end controllers that integrate equipment from the frontend tier with the supervisory control system. Depending on the development approach on the frontend tier, the following integration approaches can be distinguished:

- **Devices developed in-house** without a dedicated local control system where the front-end controller

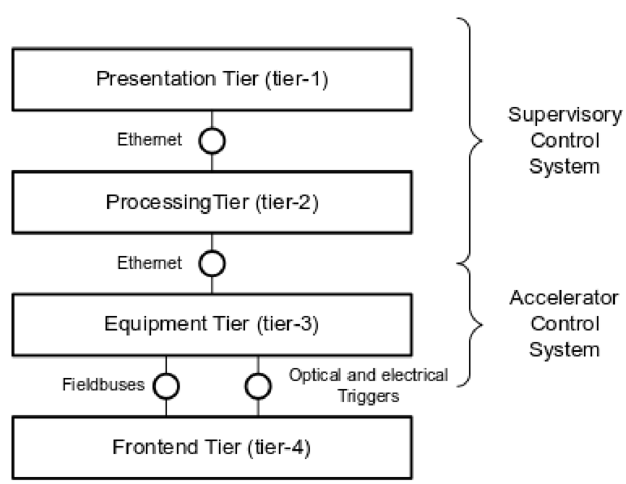

Figure 3: LIGHT control system architecture.

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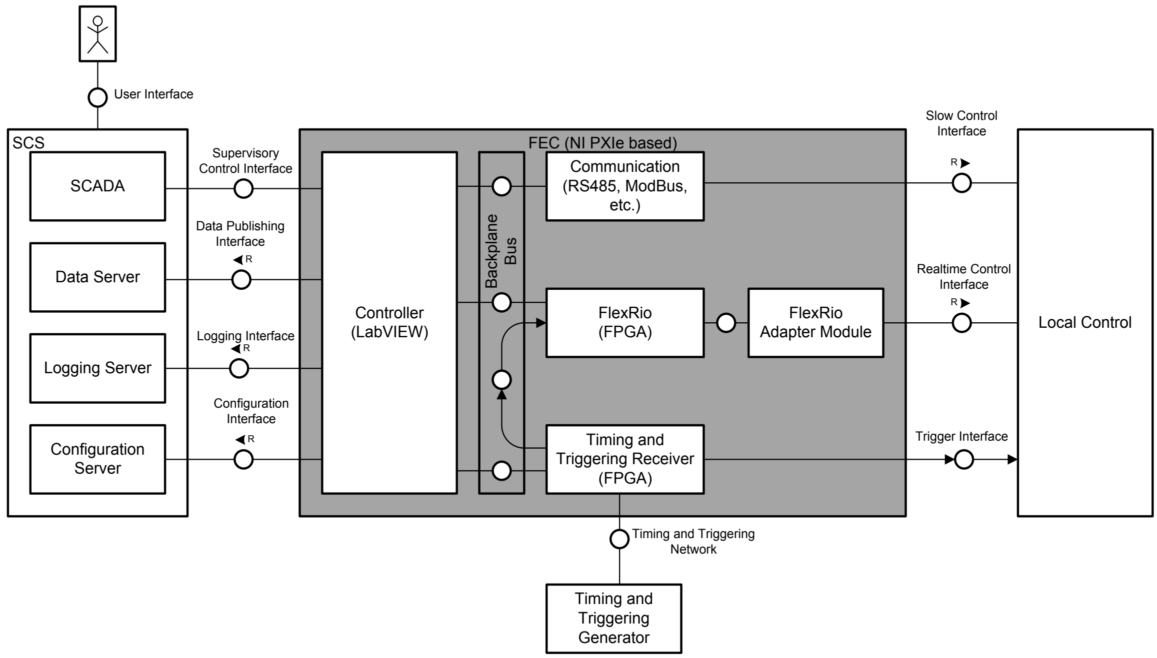

Figure 4: Front-End Controller (FEC) layout based on National Instruments platforms.

FEC) on tier-3 implements the local control system, for example for beam diagnostics devices.

- **Devices provided by supplier** but without a dedicated local control system where the FEC on tier-3 also implements the local control system, for example for cooling and vacuum systems.
- **Local control system** provided by supplier where the FEC integrates through supplier specific slow, real-time and trigger interfaces as outlined in Figure 4, for example source and power converter systems.

Front-end controllers are to be implemented either using National Instruments and Siemens hardware. Both suppliers support short time-to-market, ensured long-term support, a wide variety of interfaces to subsystems.

National Instruments PXIe platform allows to integrate accelerator systems that need triggers and real-time control which allows tight integration of real-time extensions with their non-real-time platform. Siemens SIMATIC S7 PLCs are used to integrate slow control systems without the need of triggers and settings that change with the properties of the beam. Siemens was chosen to reduce the overall hardware stack as the safety relevant systems are also implemented, using S7 PLCs.

Real-Time Front-End Controller

National Instruments PXIe systems are used as FECs when there is no need to generate interlocks but that need to change settings at 200Hz and may require triggers.

Real-time control and monitoring will be implemented on FlexRIO platform with embedded FPGAs to ensure deterministic behaviour of time-critical systems. Synchronised with the timing system, FlexRIO cards reconfigure and trigger the accelerator hardware at a frequency of 200 Hz.

Slow control and monitoring will be implemented as a LabVIEW application on the controller, relying on the "Modular Accelerator Device Integration Environment" (MADIE), an object-oriented LabVIEW framework by Cosylab [4]. Its main functionality includes:

- **Support FEC development** by providing libraries shared by multiple FECs.
- **Unified interfaces** to services in the processing tier.
- **Modularity and Extensibility** through a plug-in based architecture to allow adding additional customer specific plug-ins such as timing and trigger system.

Slow Front-End Controller

A slow control framework for PLCs with the same interface to tier 2 as MADIE is under development. The slow FECs are used for equipment which does not require real-time functionality or triggers, such as ancillary systems and systems with static settings. They are developed in a modular approach without re-programming the software to support different accelerator layouts.

Timing and Triggering System

Equipment is intended to be synchronised using a MicroResearch Finland based [5] timing and triggering system (TTS) which provides:

- **Sub-microsecond timestamping** of triggers and measurements on each National Instruments system.
- **Triggers** for processing and frontend tier equipment with a sub-nanosecond accuracy.

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- **Distribution of Beam Requests** to all equipment to apply settings specific to beam parameters.

The TTS has a central timing and triggering generator (TTG) fed by a GPS clock and a timing and triggering receiver (TTR) card in each timing slot of National Instruments PXIe crates that require triggers or pulsed operation. The TTG generates reconfiguration requests that are distributed through an optical fan-out/concentrator box to the TTRs which forwards reconfiguration requests and triggers through a backplane bus or auxiliary outputs connected to the frontend tier.

Supervisory Control System

The processing tier contains services which provide a uniform interface to configure, control and monitor front-end controllers in the equipment tier. The main services include WinCC OA as a SCADA system and a publisher subscriber called Data Server. Data from these services are archived in a database which can be used by a reporting tool to generate statistical information about the system. In addition, an offline element database that contains all types, instances and settings is planned. During reconfiguration of the system, information from the element database is exported and systems in all three tiers are configured accordingly.

The presentation tier provides graphical applications to control and monitor services in the processing tier and frontend controllers in the equipment tier. Graphical applications do not directly interact with front-end controllers but use services in the processing tier. Graphical applications are primarily implemented as WinCC OA panels and run on Windows based operator consoles. An example is outlined in Figure 5. Procedures are executed in a container in the processing tier and procedure user interfaces are executed as widgets within a WinCC OA user interface manager.

LIGHT INTERLOCK SYSTEMS

The Interlock Systems reduce the risk of harm to the personnel and the machine caused by erroneous situations or conflicting commands [6]. The protection of the patient from unintended or stray radiation and the protection of the devices from internal malfunction are outside the scope of these systems. The general layout and connections of the Interlock Systems are depicted in Figure 6.

The main requirements include:

- **Mode independency** is required for the interlock systems to react the same way in all accelerator modes.
- **Uniform interlock interfaces** for the compatibility of all devices to the interlock system.
- **Failsafe interface design** assures the safe state of the connected equipment upon a disconnected wire or a wire break.
- **Manual acknowledgement** of the interlocks by an operator is required to reset the interlocks upon a resolved interlock condition.

Patrol Safety System

The scope of the Patrol Safety System (PSS) is to assist the patrol of a room and indicate room accessibility to the machine and personnel safety system (MPSS). The PSS signals the start and the successful end of a patrol procedure to the access control system. Checking of user roles is the responsibility of the access control system. The patrol procedure consists of opening and closing a door, inspection of the area and pressing patrol buttons in the correct order within a fixed time. The safe status of a room for irradiation is established after the successful execution of the patrol procedure. If the door to the bunker is opened the MPSS immediately trips an interlock to bring all systems into a safe state to reduce the risk of harm to personnel. The PSS is implemented on Siemens SIMATIC S7 PLCs.

Machine and Personnel Safety System

The Machine and Personnel Safety system is an

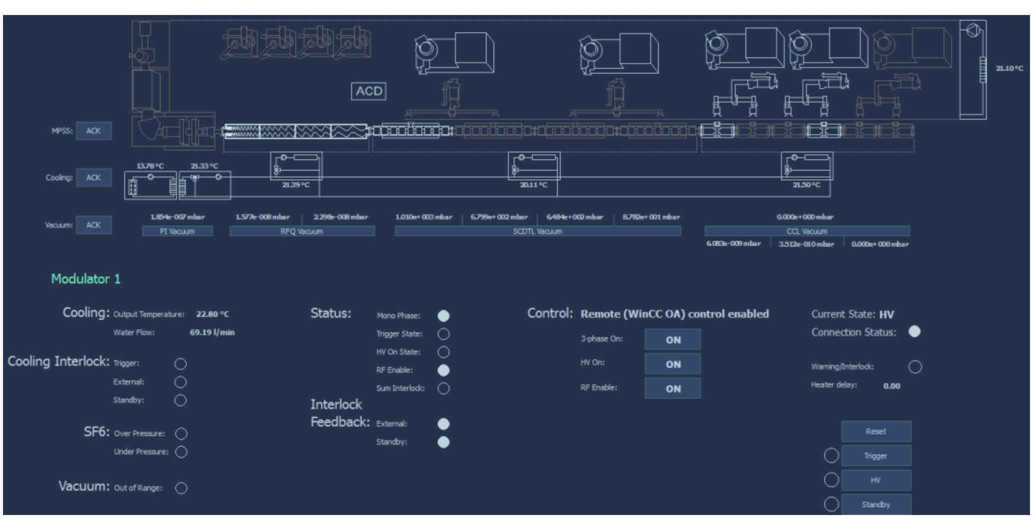

Figure 5: User interface example for the LIGHT accelerator.

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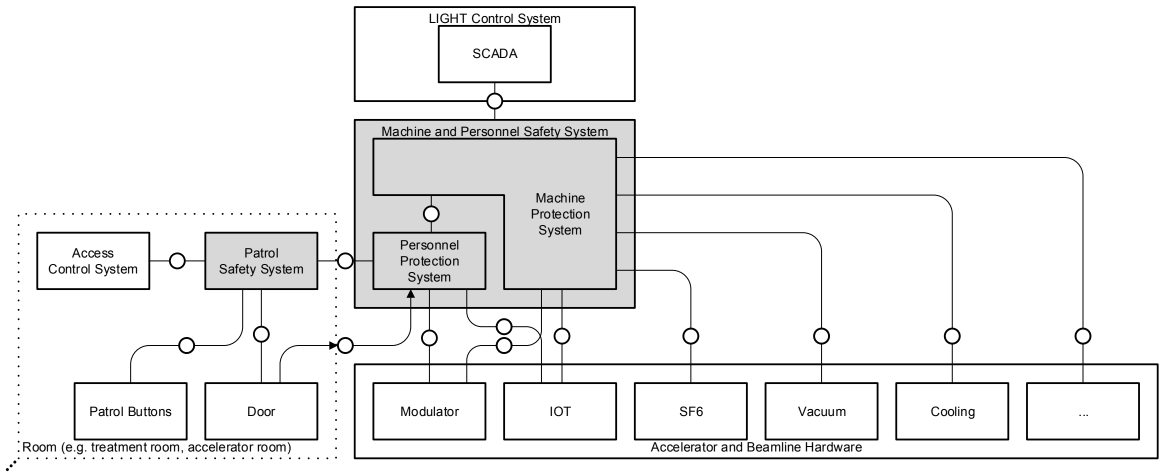

Figure 6: Example of the general layout and connections of the LIGHT Interlock Systems (grey).

interlock system to reduce the risk for personnel and the accelerator devices from harm caused by conflicting commands, malfunctioning of accelerator devices or unintended irradiation. This functionality must be provided in any state or mode of the accelerator, independently of the operation (medical, commissioning, etc.). Therefore, the MPSS must be an orthogonal system to the accelerator control systems and it must be independent of the accelerator modes or states.

The MPSS collects interlock signals from a number of sub-systems/devices and upon evaluation of the internal interlock chains it re-generates interlock signals for distribution to all the sub-systems/devices that are connected. To avoid hazardous situations each device/sub-system is responsible for the generation of status information for the MPSS and to react on the interlock signals received from the MPSS. The definition of facility-wide safety mechanisms for risk reduction purposes using interlock signals is defined at the MPSS level.

The MPSS consists of two parts:

- **Personnel Protection System (PPS)** is responsible to minimize the risk of unintended exposure to ionizing radiation for personnel when entering the accelerator and treatment rooms.
- **Machine Protection System (MPS)** is responsible to reduce the risk to the accelerator equipment of harm caused by erroneous situations.

The MPSS is implemented on Siemens SIMATIC S7 PLCs with the PPS running in the fail-safe part of the PLC and the MPS part in the non-failsafe part. The anticipated maximum reaction time is approximately 500 milliseconds.

CONCLUSION

Developing a particle accelerator for medical purposes is a challenging task for a number of reasons. Other than being a very complex device, it must also surpass the competing products on an extremely competitive market.

This article presented the overall architecture for the LIGHT control and interlock systems. The multi-tier architecture as deployed in state-of-the-art medical accelerators is used as a basis and further extended to deal with challenging requirements such as short time to market and a beam pulse repetition rate of 200Hz.

Using National Instruments and Siemens solutions at its core and the presented architecture will allow us to minimise the time-to-market and offer state-of-the-art proton therapy system with a stable long-term support.

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