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Development of the target safety system for the ESS target station

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Abstract. The European Spallation source (ESS) will be a 5 MW neutron spallation research facility where an energetic proton beam incident upon a helium-cooled tungsten target is converted to neutron beams. The liquid hydrogen moderator, water moderator, and reflector systems within the target monolith slow down the high-energy neutrons, produced through the spallation process, to cold and thermal neutrons suitable for use by experiments. Several layers of control, protection, and safety systems will be implemented in order to ensure safe operation of this advanced facility. The Target Safety System (TSS) is dedicated to the nuclear safety functions of protecting the public from exposure to unsafe levels of radiation and preventing the release of radioactive material beyond permissible limits. It is a safety-rated monitoring and control system subject to the highest reliability demands in ESS operation. In the event of an abnormal situation, the TSS guarantees that the target station operates within the design domain. It is likely that the TSS will trigger and control internal and external mitigation functions including termination of proton beam production. This paper will describe the development of the TSS, including the definition of requirements utilizing hazard analyses of all target station systems, evaluation of interfaces with accelerator and control systems, and development of the design logic.

1. Introduction

The European Spallation Source (ESS) will be a 5 MW high-power, long-pulse neutron spallation research facility. The ESS linear accelerator produces an energetic proton beam at a repetition rate of 14 Hz. A series of raster magnets ultimately directs the beam onto a helium-cooled rotating tungsten target located in the ESS target monolith, thereby producing high-energy neutrons through the spallation process. Several high-level ESS beam and target parameters are given in table 1. The liquid hydrogen moderator, water moderator, and reflector systems within the monolith surround the neutron production area of the target and convert these high-energy neutrons into cold and thermal neutrons suitable for use by experiments. Several layers of control, protection, and safety systems, including the Target Safety System (TSS), will be implemented in order to ensure safe operation of this advanced facility.

1.1. Target Station

The target monolith[1] is designed to convert protons from the accelerator into neutrons of the appropriate energy spectrum for use in experiments while providing sufficient shielding to contain radioactive by-products produced in the target and to reduce neutron background in the experimental hall. The monolith houses the rotating tungsten target along with several plugs containing the moderators and reflectors, proton beam instrumentation, target monitoring equipment, and the proton beam window which separates the vacuum environment of the accelerator from the helium environment in the monolith. Beam guides within the neutron beam extraction lines transport intense thermal and cold neutron beams from the target to each neutron-scattering instrument in the

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experimental hall. Figure 1 shows a cross section of the target monolith with the location of these systems and plugs identified.

Table 1. High-level parameters for the ESS beam and target.

Beam Parameter	Value	Target Parameter	Value
Average Beam Power	5 MW	Target material	Tungsten
Macro-pulse length	2.86 ms	Target wheel size	2.5 m diameter
Proton kinetic energy	2 GeV	Rotation rate	25.5 rpm
Pulse repetition rate	14 Hz	Estimated lifetime	5-10 years

The 2.5 m diameter target wheel within the monolith consists of 33 helium gas-cooled sectors of tungsten. Proton beam pulses from the accelerator are synchronized with the rotation of the target, with each sector receiving a rastered beam pulse every 2.4 seconds. The odd number of sectors prevents the beam from inadvertently passing through the helium cooling channels in the event that a desynchronized beam pulse impacts the target between sectors. The tungsten target transforms the incoming protons into fast neutrons through spallation, while also producing heat, radioactive isotopes and prompt radiation. The estimated operational lifetime of a full target assembly is 5 years.

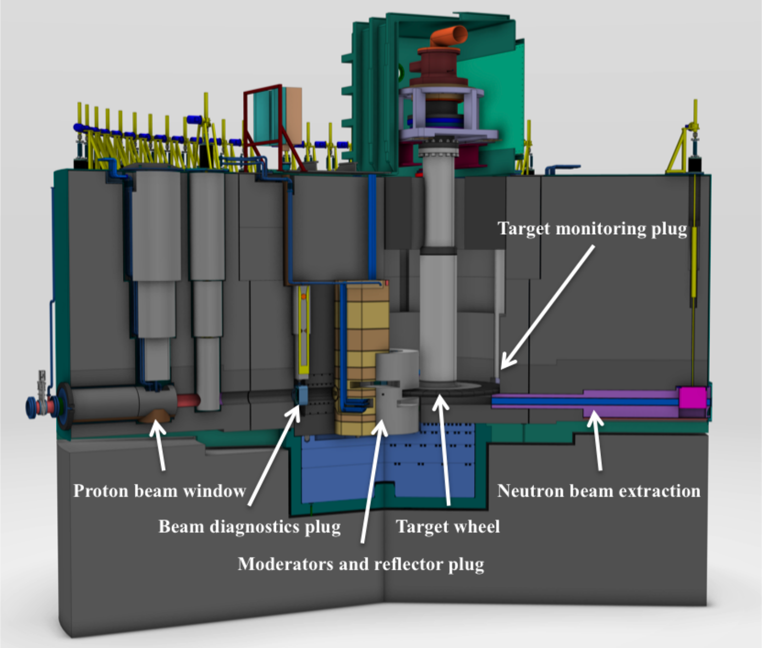


Figure 1. Cross section view of the ESS target station monolith showing the layout of important components including the target wheel, moderator and reflector plug, instrumentation plugs and neutron beam extraction lines. In this view, the proton beam enters the monolith from the left.

The moderator-reflector assembly surrounds the upstream portion of the target and converts the fast neutrons into cold and thermal neutrons. During this process, absorption of neutrons by target structures produces radioactive waste. The cold moderators in the monolith contain liquid hydrogen and have an estimated operational lifetime of 2-5 years. It is anticipated that it will be necessary to replace the moderator assembly more often than the target assembly.

Surrounding the target, moderator-reflector plug, and all target components is approximately 7000 tons of steel radiation shielding designed to contain the highly penetrating gamma and fast neutron radiation created in the target. This is complemented by additional concrete shielding to absorb thermal and cold neutrons. In total, the target monolith is a 10 m high and 11 m diameter cylinder located in the ESS target building.

1.2. Target Station Building

The target monolith is housed within the target building as shown in figure 2. In addition to the monolith, equipment necessary for target component operation including fluid systems, filtering systems, and cooling systems is located in utility rooms. The active cells area, used for handling, processing, and storage of activated target components, is also located within the target building. Target components, including the wheel assembly and moderator-reflector plug, will be removed from the monolith and brought by crane to the processing cell through the high bay. There the equipment will be disassembled using remote handling techniques in preparation for local storage in the adjacent maintenance cell until such time as the material is ready for transport off site.

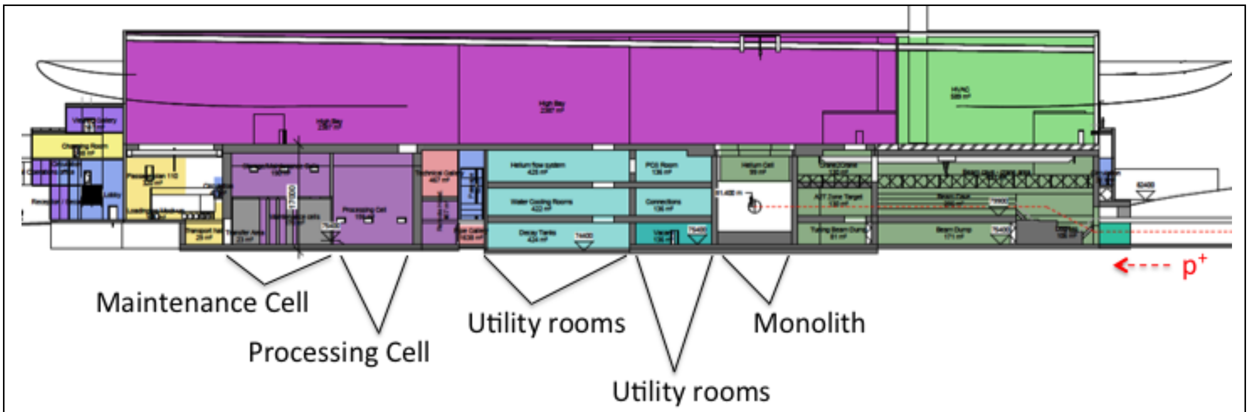


Figure 2. Side view of the ESS target building monolith showing the location of target station equipment including the target monolith, utility rooms housing equipment necessary for target component operation, and the high bay running the length of the building. The active cells area for handling of radioactive target components includes the processing cell, maintenance cell, and remote handling galleries. In this view, the proton beam enters the target area from the right, either continuing at accelerator level to the beam dump or stepping up to monolith level to the target wheel.

Additionally, figure 2 shows that there are two paths available for the proton beam into the target building. The beam can either continue to the beam dump, located at the same elevation as the accelerator, for beam studies or it can be raised to target level and continue to the monolith for neutron production. Ventilation systems for all areas are also housed in several locations within the building.

Putting the entire facility in context, the ESS is being designed and built in Lund, Sweden. This is a region with approximately 100,000 inhabitants. Additionally, there will be 450 – 500 ESS employees and roughly 3000 users per year involved with nuclear spallation experiments. All target station systems and the inventory of radioactive material must be taken into consideration from a safety perspective to assess possible risks and to evaluate the potential need for safety-related controls.

2. Target Safety System

The Target Safety System (TSS) is dedicated to the nuclear safety functions of protecting the public and workers from exposure to unsafe levels of radiation and preventing the release of radioactive material beyond permissible limits. It is a safety-rated monitoring and control system subject to the highest reliability demands in ESS operation. In the event of an abnormal situation, the TSS guarantees that the target station will operate within the design domain. It is likely that the TSS will trigger and control internal and external mitigation functions including termination of proton beam production. The TSS is subject to the highest reliability and quality assurance demands for any control system at the ESS, and will be separate from all other control systems. As a safety-credited system, the Target Safety System is an essential component of the licensing process for the ESS.

2.1. TSS context

The TSS operates independently alongside other control systems within the target station: the normal monitoring and process control, the Machine Protection System (MPS), and the Personnel Safety

System (PSS) [2]. At the ESS, all non-safety monitoring and process control for equipment throughout the facility will be integrated into one unified control system by the Integrated Control System (ICS) division. A standardized control framework, EPICS (Experimental Physics and Industrial Control System) [3], has been chosen for this system. EPICS has been used at many large-scale scientific projects world-wide and provides an excellent basis for platform standardization, device integration, and control development. The EPICS system provides control services for several modes of operations, monitoring and controls archiving, and data logging for target station equipment.

The remaining control systems at the ESS, and specifically, within the target station, have specialized scope and requirements for increasing levels of reliability and quality assurance as shown in figure 3. The MPS is designed to protect equipment from damage due to malfunction or errant beam loss, thereby protecting the investment in the facility and optimizing machine performance. The PSS is a safety system designed to protect personnel from radiological hazards primarily by controlling access to restricted areas. The TSS will limit the transfer of radioactive contamination to the public, workers, and the environment and does not depend on elements of any other controls system to perform its safety functions. Additionally, the TSS is the only controls system within the ESS that does not fall under the responsibility of the ICS division.

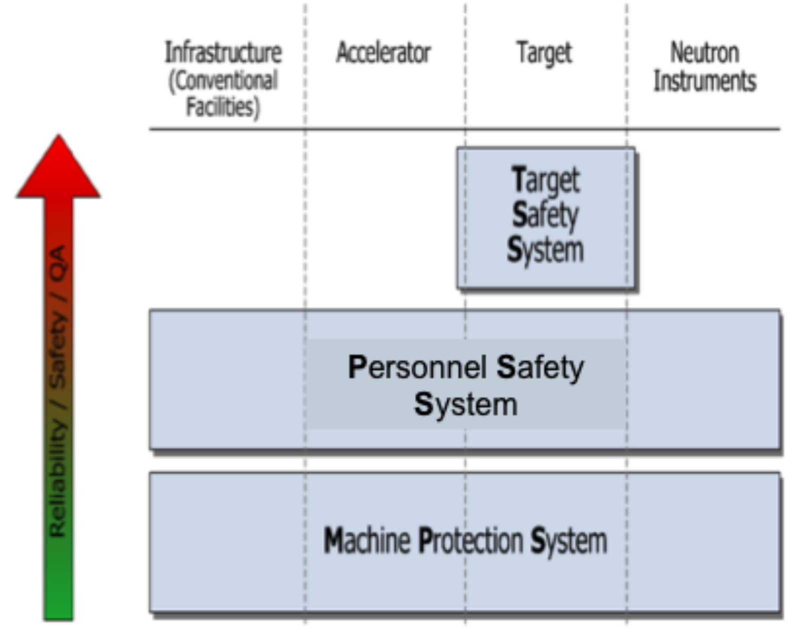


Figure 3. Representation of the main safety controls systems (Target Safety System and Personnel Safety System) and damage prevention controls system (Machine Protection System) showing scope of involvement and respective requirements for reliability.

The MPS is a machine protection system designed to optimize operational efficiency, facility availability, and machine reliability. This system will stop the proton beam in the event of equipment failures, prevent damage to elements in the accelerator and target, and provide tools for failure tracing throughout the machine. As such, it is not a safety-classified system; however, the MPS does contribute to the layered approach to safety by triggering alarms and actions, such as performing an emergency shutdown of the beam, when target station systems are detected to be operating outside of permitted ranges. The MPS has the capability to shut down the proton beam very quickly (~10 μs) and will have a high level of reliability. In contrast to the TSS, which has no requirement on post-trigger machine availability, operation of the facility must be possible in the event of any MPS action.

The PSS is a safety-classified system designed to protect personnel against unnecessary exposure to hazards from the machine, including but not exclusive to radioactivity and electromagnetic radiation. PSS systems will be installed throughout the ESS and will control access to restricted areas within the accelerator, target station, and instruments. PSS systems will be concerned with access control, radiation monitoring, oxygen deficiency monitoring, and alarm systems. Protection from radiation generated by the beams will be achieved by shutting down the proton beam upon detection of unacceptable conditions. The PSS will monitor doors, locks, and other access points to ensure they remain closed during ESS operations. Entrance to and egress from radiation-controlled areas will be managed by the PSS according to classifications defined according to different operational modes of the facility.

2.2. TSS requirements

As shown in figure 3, the TSS is the safety system subject to the highest reliability requirements within the ESS controls system domain. The TSS guarantees that the target systems operate within the design domain, and it will bring the target station into a safe state from a nuclear safety perspective in the event of an abnormal event. This will reduce the risk of harm to workers, the public, and the environment. Requirements for TSS monitoring and actions are currently being analysed. It is anticipated that the TSS will need to be able to perform an emergency shutdown of the proton beam. However, actions are not necessarily restricted to beam shutdown.

Preliminary top-level design and test requirements for the TSS have been identified and include the following:

- Single failure criterion,
- Fail-safe principle,
- Emergency power supply coverage for TSS equipment,
- Qualified for extreme operating conditions, including seismic classification for a subset of TSS functions,
- Physical separation and fire protection,
- Pre-operational testing, and
- Periodic testing of TSS equipment.

In more detail, there must be no single point of failure vulnerability within the TSS system. This implies the use of layers of redundancy, independence, and diversity along with physical separation adapted to different potential aggressors. For each hazardous scenario identified during the hazard analysis process, the safe state for the target station must be clearly identified. TSS actions will default to this safe state and actuator commands will be 'de-energize to trip' rather than the reverse. For example, in the event of a loss of power, TSS actuators will default to the safe position. The nature of the emergency power supply coverage for the TSS has yet to be determined. This will depend on the time-scale for TSS continued monitoring and actions within all identified hazard scenarios. Additionally, in contrast to the MPS, there is no post-trip machine availability requirement for the TSS. It is anticipated that a detailed analysis of any scenario involving an action by the TSS would be necessary prior to a facility restart.

Applying the top-level requirements allows the development of initial design concepts for the TSS system. There will be two independent shutdown mechanisms to stop the proton beam. Shutdown of the beam will be accomplished using both the ion source and RFQ (radio-frequency quadrupole) in the front end of the accelerator. The TSS will have direct access to these elements. Priority will be given to the TSS over the PSS and/or MPS for control of the shutdown mechanisms in the event that these systems also choose to achieve proton beam shutdown using the same accelerator components. The TSS design is based on using highly reliable safety-rated PLCs (programmable logic controller). There will be two separate TSS rooms in the target building housing redundant, independent PLC systems. There will be independent paths to each beam shut-off system: one through the accelerator tunnel and another through the klystron gallery. The TSS rooms have been identified in the ESS conventional facilities plan, and details of the cable paths from each room to both beam shutdown locations are being developed. The TSS will be separate from other non-safety controls systems and equipment, and will require independent cable-trays, UPSs (uninterruptable power supplies), and sensors.

The overarching philosophy for TSS design development enables the satisfying of safety requirements and the protection of workers and the public with a system that is as simple as possible in order to achieve a very high level of reliability. At this time, the shutdown of the proton beam is the only specific action identified as a requirement for the TSS. However, additional target-specific monitoring and controls actions may be required within systems such as the He cooling for the target wheel, wheel motion, and ventilation for target areas. Detailed requirements for TSS monitoring and actions are currently being determined using the Hazard Analysis process.

3. Hazard Analyses

Hazard analyses are being performed on all target station systems. This tool is used to understand potential hazardous scenarios within the ESS target station and to define necessary mitigations. Initially, a qualitative hazard analysis is done for each system under evaluation. This produces design recommendations for the target station systems and study recommendations to allow for the quantitative evaluation of hazardous scenario consequences. When analysed from a radiation safety perspective, mitigations may include requirements for active controls system intervention. In this way, inputs and outputs for the TSS are identified, TSS requirements are defined, and the TSS logic design and architecture can be developed.

Information from relevant studies and modifications to component design is then fed back into a quantitative hazard analysis where a more rigorous analysis can be performed. Given that most target station systems are in the preliminary design phase, this iterative process is necessary and accommodates evolutions in design and the implementation of recommendations from earlier safety analysis.

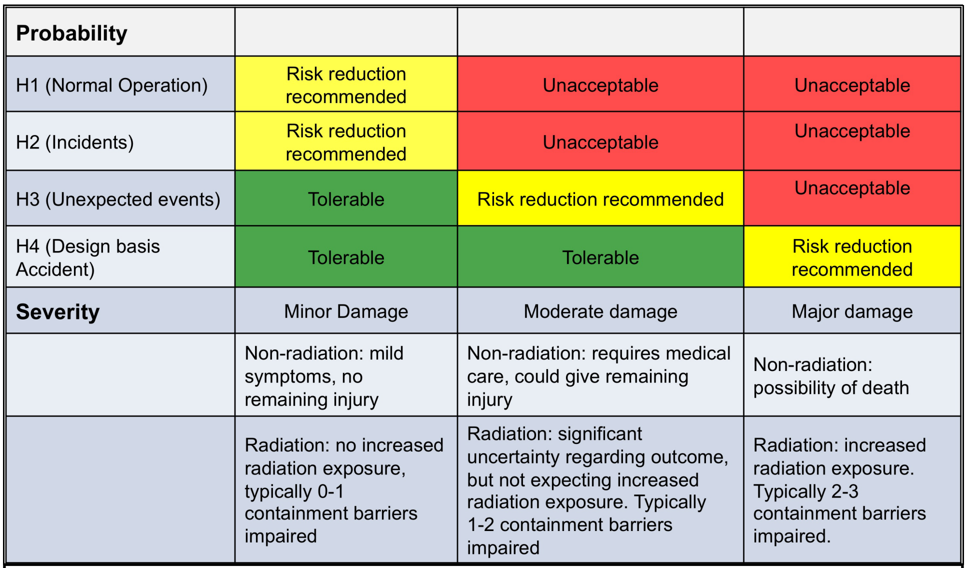
3.1. Hazard analysis procedure

There are many steps required in the hazard analysis procedure. First, the system under analysis is defined. This may include the production of drawings or schematics as well as a written description of the system including assumptions made for the purpose of the analysis. This also includes the definition of boundaries to the system under analysis and the description of relevant interfaces. In this way, the hazard analyses can be broken down into smaller; more easily understood systems. Next, hazards relevant to the system under study are identified. These include but are not limited to radioactivity, stored energy, explosion, impact such as a load drop, and hazards from the proton beam. The effects of rare events including earthquakes, fire, and an airplane crash are also evaluated.

Next, for each target station system, initiating events and top events are identified. Top events are instances of faults within the system that could produce a hazardous situation. Initiating events are actions, incidents, or occurrences leading to a given top event. For example, a top event could be the leak of air from the processing cell to the galleries. Possible initiating events could include the removal of a through-wall manipulator, a seal failure, loss of power to the ventilation system, or the erroneous opening of an access point. For each system, there are likely to be multiple top events identified during the hazard analysis. In order to understand the potential impact of each top event, the consequences without mitigation are described.

Once the consequences are understood, an unmitigated risk ranking is assigned to each top event. This is determined as a function of the probability that the top event will occur and the severity of the unmitigated consequences in the event of an occurrence. Figure 4 shows the grid used to determine the risk rankings. Probability of occurrence ranges from H1 to H4 with the probability decreasing by at least one order of magnitude for each level. For the qualitative analysis, the selected probability is largely based on expert engineering knowledge for similar systems. The severity is determined based on the consequences and differs when performing the analysis from a radiation safety perspective compared to other hazards. Table 2 shows the radiation exposure limits for both workers and the public as defined in the ESS General Safety Objectives (GSO) and the limits required by the Swedish radiation authority (SSM). Limits are listed for each category of event from H1-H4. If different initiating events have different probabilities to occur, the risk ranking for each is evaluated separately. If they are of the same order of magnitude, grouping of events can be done.

As shown in figure 4, some risk rankings are unacceptable and, therefore, require mitigation. Others indicate a recommendation for the reduction of the risk, while the low probability-low severity events are tolerable as is and do not require risk reduction. For those events not in the tolerable category, the next step in the hazard analysis is to identify applicable mitigations for each top event. These could be in the form of design changes or recommendations designed to reduce the probability of occurrence or the severity of the resulting consequences. Associated triggers for active safety system intervention can also be included as a mitigating factor to reduce the probability of occurrence. In this way, requirements for TSS monitoring and actions are identified. Once mitigation factors are identified, the risk ranking is reassessed, taking into consideration the effect of the mitigations on probability and/or severity of occurrence of the top event. If the risk ranking still does not fall into the tolerable range during this re-evaluation, then further mitigation is likely to be necessary.



Probability			
H1 (Normal Operation)	Risk reduction recommended	Unacceptable	Unacceptable
H2 (Incidents)	Risk reduction recommended	Unacceptable	Unacceptable
H3 (Unexpected events)	Tolerable	Risk reduction recommended	Unacceptable
H4 (Design basis Accident)	Tolerable	Tolerable	Risk reduction recommended
Severity	Minor Damage	Moderate damage	Major damage
	Non-radiation: mild symptoms, no remaining injury	Non-radiation: requires medical care, could give remaining injury	Non-radiation: possibility of death
	Radiation: no increased radiation exposure, typically 0-1 containment barriers impaired	Radiation: significant uncertainty regarding outcome, but not expecting increased radiation exposure. Typically 1-2 containment barriers impaired	Radiation: increased radiation exposure. Typically 2-3 containment barriers impaired.

Figure 4. Categories used for determining the risk ranking for top events during the hazard analysis process. Probability of occurrence categories range from H1-H4 in decreasing probability.

Table 2. Radiation exposure limits as defined in the ESS safety objectives and those required by the Swedish radiation authority (SSM) for different categories of events.

	From the ESS General Safety Objectives		From SSM
Event likelihood	Worker Limit (Effective dose)	Public Limit (Effective dose)	Public limit
Normal operation – H1	10 mSv/year	0.05 mSv/year	0.1 mSv
Incidents – H2 $10^{-2} <$ Probability	20 mSv/event	0.5 mSv/occurrence	1 mSv
Unanticipated events – H3 $10^{-4} <$ Probability $< 10^{-2}$	50 mSv/event	5 mSv/occurrence	10 mSv
Design basis accident – H4 $10^{-6} <$ Probability $< 10^{-4}$	50 mSv/event	20 mSv/occurrence	100 mSv

3.2. Hazard analyses status

A comprehensive hazard analysis is being done on the ESS target station. Monolith systems under evaluation during this process include the cold moderator, water moderator, reflector, monolith, proton beam window, and target system. For each of these, the relevant primary fluid systems are also evaluated. In this case, the target system is defined as the wheel, the drive, and the target helium cooling system. Those parts of the target station that are not located within the monolith are also evaluated in order to develop a comprehensive safety case. These include the ventilation systems for different parts of the target building, intermediate cooling systems, the beam dump, active cells, remote handling, and an analysis focused specifically on proton beam-induced events.

The initial qualitative hazard analysis has been done for the following systems: water moderator, cold moderator, reflector, and target system. Analysis is in progress for the active cells and ventilation systems with remote handling and beam events next in the queue. The proton beam window (PBW), redesigned monolith, active liquid and gaseous storage, and beam dump systems hazard analyses will follow. The first systems involved in the qualitative analysis will soon be revisited with a quantitative hazard analysis, incorporating design recommendations and results from the initial studies. Documentation will be formalized and updated, events will be grouped as appropriate, and TSS requirements will be finalized and logic refined. The preliminary design review of the TSS logic is planned for 2015 with the critical design review of the TSS system in 2016. Manufacturing, installation, and commissioning will follow with the goal of producing the first beam on target in 2019.

4. Interfaces

As part of the development of the TSS, interfaces with systems both internal and external to the target station must be evaluated and defined. Interfaces with target station systems are determined by the hazard analysis process and may include sensors, actuators, and data monitoring and tracking. As it is necessary for the TSS to shut down the proton beam, there are naturally interfaces with the ion source and RFQ in the front end of the accelerator. The TSS group is collaborating with the accelerator group to define the interfaces and to optimize the beam shutdown mechanisms. Other potential interfaces between the TSS and the accelerator are under evaluation. These could include components such as the bending magnets that determine whether beam is sent to the target or the beam dump.

One of the most urgent interfaces that must be clearly defined is that between the TSS and conventional facilities. Construction on the ESS has begun recently, and time is short to identify interfaces that impact building design and construction. Requirements for the TSS rooms including cooling needs, intended occupancy, fire prevention, and security access have been defined. Additionally, the effort to identify the optimal TSS cable paths from the target building rooms to the accelerator front end and cable requirements has intensified.

Finally, all interfaces between target systems and ICS systems are being defined. Figure 5 shows a preliminary overview cartoon representation of these interfaces. As part of this process, interfaces between the TSS and other controls systems including the MPS and PSS are being evaluated. The TSS will have independent components such as PLCs, sensors, actuators, cables, cable trays, and will not have inputs from other controls systems. However, it is possible that the TSS will send a signal verifying that it is functional to the target MPS for incorporation into the beam permit system. The TSS may also send data into EPICS via the ICS control box, thereby enabling the use of the archiving tool. Evaluation of these potential interfaces and determination of possible methods for execution while maintaining the high reliability level required for the TSS is on-going. No interfaces between the TSS and PSS are foreseen at this time.

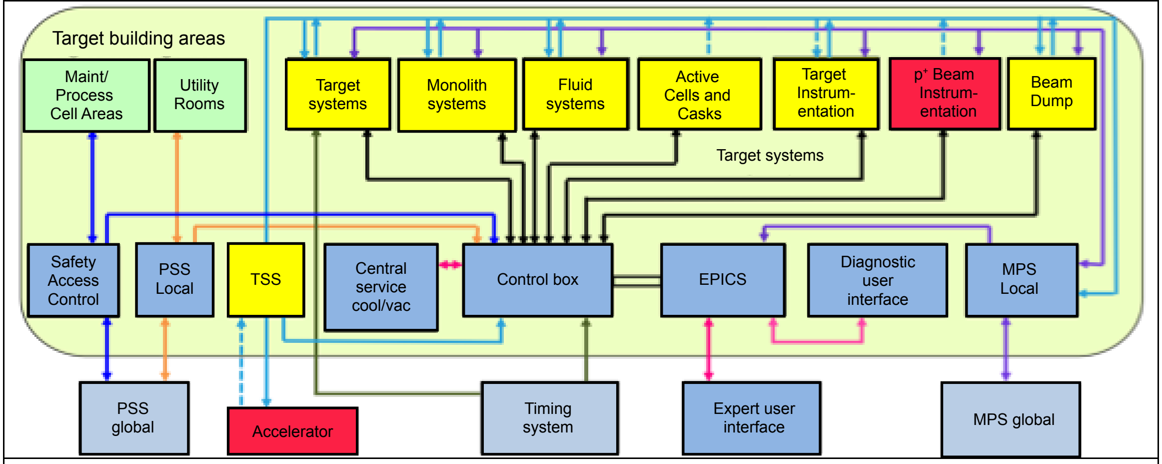


Figure 5. Overview of interfaces between systems within the target station and building and ICS controls systems including standard operations controls within EPICS, MPS, and PSS.

5. Conclusion

The process to derive the set of Target Safety System controls has been developed and is well under way. The TSS purpose within the global safety plan is understood as is the division of scope between it and the other controls systems at the ESS. Qualitative hazard analyses are being executed in order to derive target station system design requirements, identify necessary studies, and determine initial TSS requirements. Further quantitative analyses will be used to refine these requirements, define the TSS logic, and build up a description of the TSS architecture where complexity will be minimized in order to meet the requirement for a very high level of reliability. Simultaneously, collaboration continues between the target, accelerator, safety, conventional facilities, and ICS groups to ensure that proper interface definitions exist for the TSS and to prepare for these interfaces as soon as possible. The final Target Safety System design is planned for 2016 with the underlying goal to protect the public from exposure to unsafe levels of radiation and prevent the release of radioactive material beyond permissible limits.

References

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