Risk analysis from a user perspective of the beamline BALDER, MAX IV Laboratory

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Abstract

The main purpose of this report is to identify, evaluate and if possible, suggest reduction methods to the risks from which users at the beamline BALDER, MAX IV Laboratory are exposed to during their visit. Identified risks includes radiation, fire, electricity, gases and miscellaneous risks such as the overhead crane. The evaluation indicates that the handling of toxic gases inside the experimental hutch is the highest risk for users to be considered at BALDER. To improve the user safety at BALDER, investigating the gas handling of gas cabinet nr. 5 is of great importance. Also, looking over the safety instruction routines for arriving users and an installment of a passage to the exp. hutch are to consider.

Contents

1 Introduction

MAX IV is a national facility with Lund University as host institute. The facility including the buildings, the linac and the storage rings costs around SEK 3 billions and is funded by the governmental agencies Swedish Research Council and Vinnova together with Lund University and Region Skane. Additional funding has been required for the different beamlines and around SEK 700 million is funded for the first seven. It is mainly made by Knut and Alice Wallenberg Foundation but also by different universities around Sweden and by some operators in Finland, Estonia and Denmark. The operating costs for MAX IV are shared by Lund University and the Swedish Research Council.

MAX IV facility is a research facility located in Lund, Sweden that will use synchrotron radiation for studying different types of samples. The light is created using accelerated electrons transferred into one of the storage rings. At certain points in the ring, the electrons are forced to loose energy and thereby emit radiation, mostly in form of X-ray photons. The samples are then irradiated in order to observe and study structures in both molecules and atoms as well as solid structures. The main strength and purpose of building MAX IV is the high brilliance of the photons for a specific energy interval, see figure 1. The construction of MAX IV started in 2010 and will be inaugurated midsummer 2016.

The MAX IV Laboratory consists today of the MAX IV facility and MAX-lab. MAX-lab itself consists of the MAX I, MAX II and the MAX III rings together with a facility for nuclear research. MAX-lab is about to be dismantled and all research activities will end in December 2015. This means that the use of the name MAX IV facility probably will be phased out as the official name MAX IV Laboratory and the unofficial short MAX IV will be used. Further on in this report, MAX IV and MAX-lab will be used for the two different facilities and the MAX IV Laboratory will be referring to both. Also users and guest scientists will refer to the same persons i.e. those who performs experiments at the MAX IV Laboratory. This is not entirely correct since staff, especially beamline staff can and are users as well but not guest scientists.

The facility of MAX IV contain very powerful instruments to produce synchrotron radiation. This will require unique safety measures for the staff and for the guest scientists. The users who visit MAX IV will probably not have, and don't want to spend valuable experimental time to learn safety regulations. Their nationalities will also be represented from all over the world, which mean they might have different knowledge and understanding of safety regulations from their own respective work places. Therefore, it is of high importance that the risks related to their work at MAX IV are identified, evaluated and reduced so that no accidents occur even when the users are stressed or tired from working long days. This report will mainly focus on risks that guest scientists (users) can encounter and how to prevent accidents from happening, meaning focus on the users and not the staff. This report will bring up the risks in a safety aspect, not a security aspect, i.e. nothing about risks of persons who create hazards intentionally.

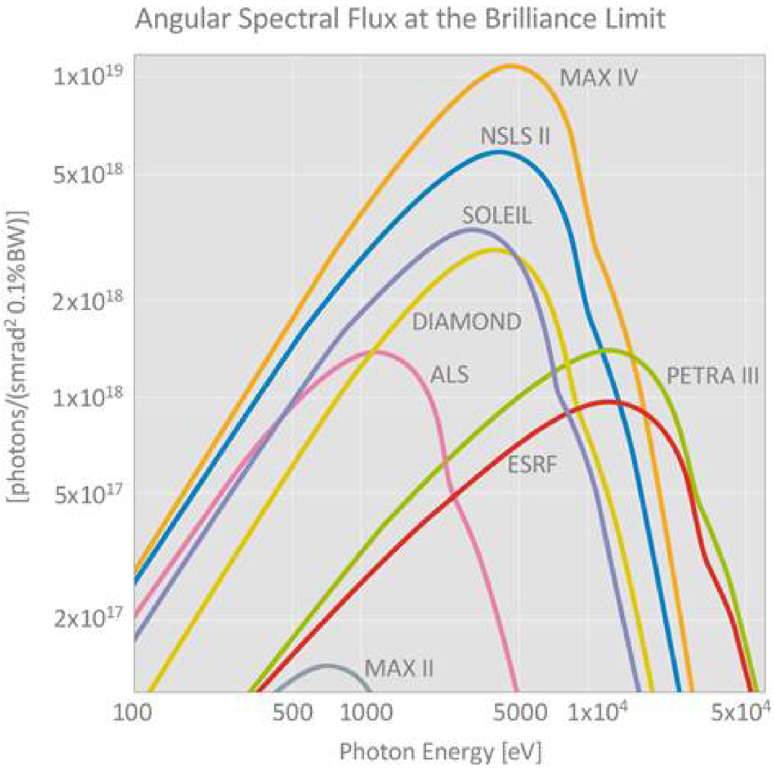

Figure 1: The figure illustrates the brilliance as a function of photon energy for some of the world leading synchrotron radiation facilities. The MAX IV Laboratory's main contribution is around 1-50 keV (corresponding to 0.4-1.2 nm in photon wavelength). [1]

1.1 Purpose

MAX IV is a facility which contains many different types of risks. The safety group at the MAX IV Laboratory, which work with risk reduction and documentation regarding safety, has seen a need of a risk analysis that focus on the users.

The main purpose of this report is to identify, evaluate and if possible, suggest reduction methods to the risks from which users are exposed to during their visit at the MAX IV facility. Since it is less complex and this analysis is within a time frame, the report will concentrate on risks related to one of the beamlines, BALDER at the 3 GeV ring. It will be focusing on aspects such as exposure to radiation, the gas system, fire and electricity to mention a few. These risks will then be identified and evaluated from a human, technological and organizational (HTO) perspective. If possible, this report may be applied to other beamlines as well. The questions this report wants to answer is:

- What type of risks are users at the beamline BALDER, MAX IV facility exposed to?
- To what magnitude are these potential risks evaluated as?

- Are there any suggestions to risk reducing measures?

Two secondary purposes are also made for this report. The first is to describe the physics and systems of how the MAX IV facility works on a master student in physics level. The second is to work as a substrate for forthcoming risk analysis reports in the future. This purpose is in a high extent linked to the main purpose since the information for the two will more or less be identical.

2 Method

The report was primarily made to identify and evaluate the risks users at the beamline Balder at MAX IV are exposed to. In order to do so, it was important to learn and understand how the MAX IV facility and BALDER work and how the research performed at the facility is carried out. Different types of methods were also made which leads to different perspectives and thereby more knowledge of how potential improvements could be like. This is the general concept of the risk analysis made for this report.

To identify potential risks at BALDER, different types of research were made; on the internet, in books and interviews with relevant staff at the site. Since the MAX IV facility is very similar to MAX-lab, it can be used in the research and investigation of MAX IV. MAX-lab was therefore used as a reference of what to expect at MAX IV regarding everything from risks, physics theory, routines and regulations etc. Also, relevant practice for four weeks was carried out at the beamline I811, since it is considered to be the most similar beamline at MAX-lab compared to BALDER. Along with the practice at I811, interviews with the safety manager, operating staff and project manager at the beamline of both i811 and at BALDER, as well as the guest scientists at the i811 were carried out. The interviews with the safety manager was continuously ongoing throughout the writing of this report, regarding technical as well as risk related issues and reasoning. Interviews with the operating staff and guest scientists has mainly been carried out during the practice at I811 while two interviews of an hour each has been made with the project manager of BALDER. Also, many visits has been made to the construction site of MAX IV. Even if MAX IV and BALDER isn't finished yet, visits to the construction site has also been made during the project in order to get an understanding how it will look like and to obtain information that can be useful during the risk analysis. This include everything from radiation safety and theoretical knowledge to the PSS (see 4.3).

In order to get another view of the risk analysis, information of the parts, systems and processes were obtained in order to see how they could affect the risks at BALDER in a positive or negative way. Especially a process description of how guest scientist (user) visit looks like was carried through. This process is described step by step from preparations before entering the MAX IV Laboratory until they leave. This process is somewhat different for different users, but in general the process remains the same. Together with this process description, a location description is produced for the locations within the site where the users will be working or visiting. This will mainly refer to the experiment hutch, the preparation lab or the control room. The purpose was then to merge the information of both description to be able to analyze what types of risks users are exposed to, and when and where they occur. A so called "Bowtie model" (see section 3.6.5) was also used in order to evaluate some of the risks and to try and identify were barriers could be implemented or improved. The identified risks was then evaluated and put into a risk matrix shown in figure 15 in the result section.

This report will not investigate the other beamlines except in a comparison with BALDER. This report will only describe the fundamental parts of MAX IV, such as the linac, the storage rings and as mentioned, the other beamlines. Other parts as the main office building, the SPF (Short Pulse Facility) and the possible future FEL (Free Electron Laser) will also not be of focus in this report. There is also a chemistry lab in the main building. Since this may be used by the scientists operating at BALDER, this will be, if only briefly and not fully analyzed, mentioned in the report. Regarding BALDER itself, the optics hutch will also only be mentioned briefly. The main reason is simply that when the beam is running, no one is allowed in most of these areas. When the beam isn't running, the guest scientist themselves are only allowed in these areas in the company of a guide with radiation protection clearance. They also don't have any purpose of operating in those areas, especially around the linac and the storage ring. The exception may be the SPF, FEL (in the future) and the main office building. The SPF and the FEL are however to consider as any other different beamlines and at the main office building, the risks are similar to any other office building. As mentioned, this report will focus on safety for the users and not on security.

3 Theory

This section is categorized in subsections describing the parts of MAX IV and its theory from the creation of electrons to the light reaches the experimental hutches at the beamlines.

3.1 Linear Accelerator - linac

The main purpose of the linac in MAX IV, see figure 2, is to accelerate electrons up to a maximum of 3.5 GeV. Firstly, the electrons are produced, which is done in two different ways. Either by heating up a cathode which releases electrons to the anode, so called thermal ionic, or by creating free electrons excited with a laser. The electrons are then directed into the linear accelerator known as the linac. To accelerate the electrons, cavities within the linac are put in sequences where an electric field is applied. The electric field is alternating sinusoidally made by a radio frequency of 3 GHz, and lined up so every other cavity has the same field direction. The electrons are then injected to match the phase of every cavity they go through in order to accelerate. Actually, the velocity of the electrons is already very close to speed of light in the very beginning of the linac. The so called acceleration process is instead made to raise the electrons relativistic mass m according to Einstein's relativistic formula for energy E, see (1).

$$E = mc^2 \tag{1}$$

The electrons can then "ride the wave" almost like a surfer to gain relativistic mass and thereby energy. The linac in MAX IV is 250 m long and placed underground. The electron beam is either directed up to ground level to the storage rings or continue below ground to the SPF (Short Pulse Facility) and eventually to the FEL (Free Electron Laser) in the future. The linac produces, accelerates and injects electrons into the storage rings every five minutes to make up for lost electrons, the so called "top up" system. This way experiments can be performed continuously at high intensities. This can be compared with the MAX II ring that only fill up electrons once every 12 hours which makes the intensity more unstable and fluctuating. [2]

Figure 2: A part of the linear accelerator at the MAX IV Laboratory. [3]

3.2 The storage rings

MAX IV has two separate rings that are supplied with electrons from the linac with circumferences of 96 and 528 meters. The smaller ring has an electron energy of 1.5 GeV and can be compared to the previous MAX II with the same electron energy and a circumference of 90 m. The bigger main ring stores 3 GeV electrons which allows other possibilities in research than the smaller ring. However, all types of experiments that are made with the MAX II ring today do not really require that high electron energy. The smaller ring therefore makes it possible to have increased capacity even when MAX II is disassembled. Further on, the ring that is referred to in this paper is the larger 3 GeV ring since it's the main reason of building MAX IV and the ring where beamline BALDER is constructed, see figure 3.

As well as in the linac, the storage ring also has cavities in which an electric field alternating sinusoidally. The purpose is however slightly different. Firstly, these cavities makes up for the energy lost while moving in the ring so it remains reasonably constant. Secondly, the cavities in the ring have a much lower frequency, which makes the electrons come together in bigger bunches. If the

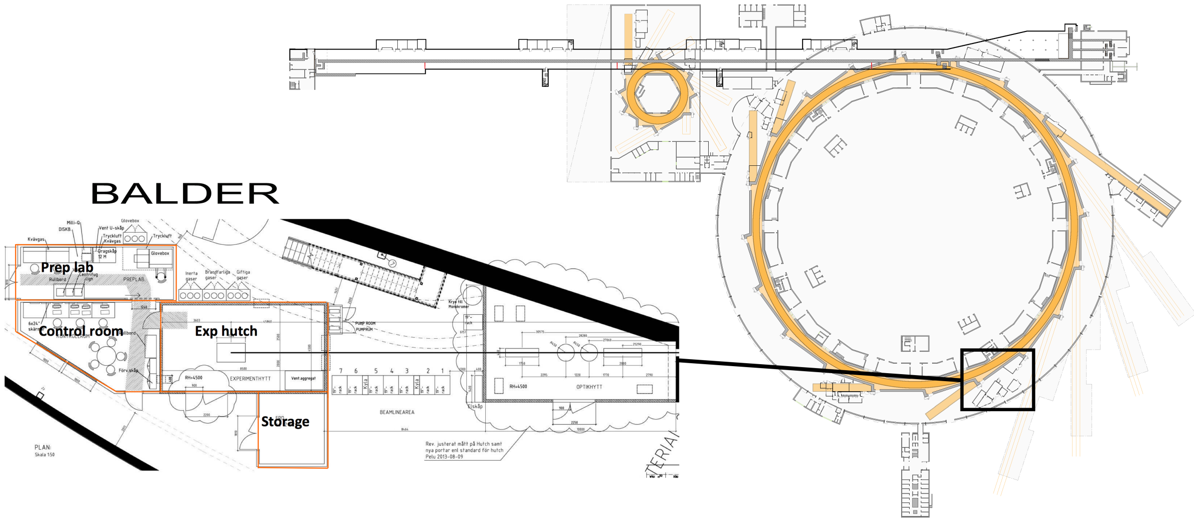

Figure 3: Floor plan of MAX IV and the beamline BALDER.

electrons are slightly slow or fast, then the electric field makes them momentarily speed up or slow down relative to its own bunch. However, if they are too slow or fast, then they will fall out and vanish from the system. This process is quite similar to "natural selection" where only the electrons arriving at the right time will survive. The electron bunches has a very short time duration, in the order of 100 ps.

Except for the cavities, the ring itself mainly consists of vacuum pipes. The vacuum pipes are surrounded by different types of magnets; dipole, quadrupole and sextupole magnets. The dipole magnets (bending magnets) keeps the electrons in its circuit and forces the electrons to bend off in the current direction. Because of the increased size of the ring compared to MAX II, the centripetal force, see (2) and thereby the reactive centrifugal force f is smaller since it decreases if the radius r increases. This is however only correct as long as the mass m don't change.

$$F = \frac{mv^2}{r} \tag{2}$$

Quadrupole (see figure 5) and sextupole magnets are used to prevent the electrons from moving out of its orbit in the circuit. However, since the electrons at this speed (close to the speed of light) are strongly affected by the Lorentz force, see (3).

$$F = q(E + v \times B) \tag{3}$$

where q is the charge, E the energy, v the velocity and B the magnetic field. This means that the magnets only can focus the beam in some of the planes at a time since F is perpendicular to v and B, see figure 4. This makes it necessary to tilt some of the focusing magnets and also use spaces between them to maintain focus of the beam. The vacuum pipe is also smaller than the one at MAX II, these two factors makes it possible to achieve the same focus and control of the beam curvature with smaller magnets. In MAX IV, these magnets are placed together on different segments that makes the alignment of the beam easier and cheaper to construct.

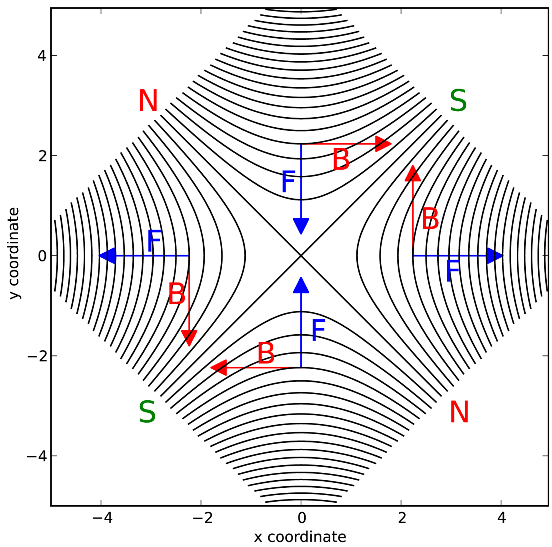

Figure 4: Magnetic field of an idealized quadrupole with forces. [6]

The MAX IV Laboratory has implemented many new techniques in order to improve the quality of the beam. The most revolutionary is perhaps the "Multi-Bend Achromat" (MBA) which bends the electron beam in many steps built in one solid block instead of using separate bending devices. This technique will reduce the emittance of the beam as well as costs compared to conventional methods. Other synchrotron facilities are today investigating or already upgrading their systems to use MBA's instead, and of newly constructed or planned synchrotron's most of them will probably use this technique. The storage ring itself will be finished in 2015. [4] [5]

3.2.1 Undulators and wigglers

Photons are emitted from the moving electrons in the storage ring when they loose energy by accelerating in the bending sections. Light from bending magnets can and is used for some experiments, for example at MAX-lab. However, this kind of light has not as high intensity or energy as may be required in some experiments. This problem is solved by so called wigglers and undulators. They are made by applying a magnetic field B that is alternating along the electrons path in the ring. This creates a transverse path in which the electrons are oscillating with the wavelength λ_u depending of the undulator/wiggler. The difference between these two is that the wiggler creates a broader spectrum of synchrotron radiation than the undulator at higher energies. However, there

Figure 5: A quadrupole magnet installed at the MAX IV Laboratory 3 GeV storage ring. [3]

isn't a straight line where it goes from a wiggler to an undulator and vice versa. This is decided by the strength parameter K which is proportional to B and λ_u, for $K >> 1$ it's called a wiggler and for $K < 1$ an undulator. In between (approximately) $1.5 < K < 5$, there is a so called transition region.

To decide whether to use an undulator or a wiggler depends on the type of light the experiment needs. The electrons through an undulator oscillates with a lower amplitude than a wiggler. This means that the emitted photons will be interacting in a higher extent and the beam will be higher focused and thereby have a higher brilliance. For an undulator, it's important to determine λ_u in order to achieve constructive interference when the photons interact. The wiggler, that uses stronger but fewer magnets, produces a much broader light with less interactions. There are also no well defined harmonics as often in the case of an undulator. However, since the bending curvature is higher, the emitted photons will have higher energy instead. As mentioned before, the type of light used depends on the experiment itself. Undulators produces a much more narrow band light with high brilliance which sometimes is more useful than the broader spectra. Undulators are also often used in the soft X-ray range to study surfaces, because at around 10 eV, the mean free path for electrons is very short and only the surface electrons make it to the detector. However, the wiggler is better to use when the experiment setup needs to be swept over energy by using a monochromator. The brilliance becomes lower but the bandwidth is larger and higher and therefore suitable for hard X-rays. The wiggler is also often better when studying complete sample properties and not only the surface since the higher energies makes the beam more penetrating. However, both techniques can be used to excite electrons in order to emit fluorescence from the sample. [7]

3.3 Beamlines

The light will be emitted from the wigglers and undulators into so called beamlines along the direction of the straight sections of the storage rings. Directly after the beam has left the storage ring, there is some kind of beam optics for focusing. This consists of a concealed room at every beamline called the optics hutch with clearance for authorized staff only. In the optics hutch, a monochromator is also often used to disperse the synchrotron light in order to sweep the sample over different well defined energies (or wavelengths). The end of most beamlines consist of an experiment hutch. Here is where scientists (users) make their experiments using different types of lights for different beamlines. Every beamline will also be slightly different from the others to enable different types of experiments. Adjacent to the exp. hutch there is a control room from where the experiment is run and the data analyzed. Sometimes they also have a preparation lab nearby in order to prepare samples for experiments. The prep. lab may also have a glove box and a fume cupboard in order to increase safety. All beamlines aren't planned yet and will be carried out in interaction with existing and future user communities. MAX IV has a capacity for 19 beamlines in the 3 GeV ring, 11 in the 1.5 GeV ring and the beamline to the SPF in the basement which doesn't enter the storage ring. Eventually a Free Electron Laser (FEL) also will be built in the basement. Even if the beamlines have the same purpose of directing synchrotron light into an exp. hutch where samples are irradiated, the beamlines may differ significantly in design depending on what type of preferred measurement technique. For example will chryotechnology with liquid nitrogen or other types of gases be used to cool the sample in order to improve the experimental results. It can also be the other way around so the samples are heated up instead to achieve specific conditions. It is also important to know which range of synchrotron light energy the experiment needs and which technique to use. Some samples may also be harmful and needs to be handled with special safety measures of the experimental setup. This report will mainly focus on the beamline called BALDER at the 3 GeV ring at MAX IV since it's considered covering most of the expected risks regarding experiments from the beamlines with the exception of lasers. The beamline is also the location where users not only perform their experiments, but monitor them and prepare their samples. For users, this is where they spend almost all their time during a visit.

3.4 BALDER

BALDER is one of the potential 19 beamlines that can be connected to the 3 GeV ring at MAX IV. BALDER has gotten its name from the god of light and purity in Norse mythology. The inauguration of BALDER is planned along with MAX IV itself in summer 2016. In the first stage only for friendly users (beta testing) and then for all users in 2017. Overall it is quite similar to the other beamlines in general with some differences. Experiments on this beamline often requires different types of gases that are used in the chamber containing a sample in the middle, or by just examine the gas itself. This will often be carried out with certain pressure around and in connection to the sample, preliminary up to a maximum of 50 bar. It will also be using an oven heating up samples to maximum 900° Celsius. BALDER uses the techniques EXAFS and XANES described below in section 3.4.1. It will use photon energies from 2.4 to 40 keV and can be considered as an improved version of the recent beamline I811 at current MAX II. I811 as well as BALDER in the near future, is often used on samples with low concentrations of substances, as low as ppm.

3.4.1 EXAFS and XANES

EXAFS stands for "Extended X-ray Absorption Fine Structure" and is one of the techniques in which BALDER will operate. It uses synchrotron light (hard X-rays) to eject core electrons by the photoelectric effect, a so called photoelectron from the sample. The atom from where the photoelectron was emitted has now turned into an excited state, and the energy of the photoelectron plus the binding energy will be equal to the absorbed photon energy. This only happens for different materials at certain energies, a so called absorption edge. When irradiating a sample with the incoming intensity I_0, it's possible to detect for which energies the intensity after the sample I make a dip. This means the transmission will decrease when the absorption increases. The absorption increases rapidly for some energies and these peaks represent the binding energy of an electron within the sample. Each element has its own set of unique absorption edges and the intensity is described by (4).

$$I = I_0 \cdot e^{-\mu x} \tag{4}$$

Where μ is the absorption coefficient and x is the sample thickness. The reason of using X-rays is mainly because they are highly penetrating and can therefore be used on solids and liquids as well as gases. However, EXAFS can also be carried out indirect on non-penetrating samples by either measuring the fluorescence of the emitted X-rays or the photoelectrons themselves. This creates an interference pattern that causes an oscillating EXAFS spectra. This is then normalized and Fourier transformed in order to determine the coordination of atoms within the sample. EXAFS is used with synchrotron light because of its energy and its high brilliance which enables samples with as low concentrations as down to ppm.

XANES, which stands for "X-ray Absorption Near Edge Structure" also known as NEXAFS ("Near Edge X-ray Absorption Fine Structure") also used at BALDER, has the same method as EXAFS but is used for specifically studying the electronic transitions. As the name tells, XANES is focused on the near edge of the spectra where atomic core ionization begins, unlike EXAFS, which mainly covers the oscillations at higher energies (up to 1500 eV above the edge). The near edge region where XANES operates is considered to be about 50-100 eV over the edge. The total spectra over XANES and EXAFS is called XAFS. [8]

3.5 Radiation

There are many types of radiation, for example electromagnetic radiation and particle radiation. Radiation can be divided into two groups: Ionizing radiation and non-ionizing radiation. Ionizing radiation has enough energy to separate electrons from atoms or molecules. The minimum ionization energy is around 10 eV to 33 eV depending on the atom or molecule. This section will mainly focus on ionizing radiation from X-rays since its the main concern at MAX IV Laboratory beamlines and any other synchrotron facility. Soft X-rays, i.e. low-energetic X-rays have an energy around 100 eV to 10 keV while hard X-rays (high-energetic X-rays) have an energy of 10 keV to 100 keV. BALDER will mostly use the hard X-ray spectrum since this is where EXAFS primarily has its region. Soft X-rays are however also used in other beamlines at MAX

IV Laboratory. When the X-ray radiation mostly occurs within the beamlines, gamma radiation is more common regarding the linac and the storage rings. In the storage rings, electrons can lose energy and fall of the closed orbit, then they hit the inner side of the pipe, slows down rapidly and produces gamma radiation. Similar event regarding the linac where electrons also falls off the lane and rapidly decrease in energy which results in gamma radiation. This is however more of a concern for the staff than the guest scientist since they usually only operate within the beamline area.

The equivalent dose for ionized radiation is measured in Sievert (Sv). The equivalent dose represents absorbed dose to an organ or tissue weighted by the weighting factor W_R which depends on the type of radiation R. Sievert is a unit in the International System of Units (SI) and represent the effects of ionized radiation outside or inside the body where 1 Sv = 1 Joule/kilogram. The equivalent absorbed dose H_T of tissue T is defined as in (5).

$$H_T = \sum_R W_R \cdot D_{W,R} \tag{5}$$

where $D_{W,R}$ is the mass-average absorbed dose in gray (Gy) in tissue T by radiation type R. H_T should not be confused with the effective dose E seen in (6) which is the sum of the equivalent doses weighted by W_T.

$$E = \sum_T W_T \cdot H_T \tag{6}$$

Often is it considered most important to analyze the effective dose since it covers the whole body regarding all organs and tissues, but in some cases the equivalent dose is as important as the effective dose. When it is known that only a specific part of the body is exposed to ionizing radiation, the effective dose may be relatively low but instead the equivalent dose is dangerously high to that specific organ or tissue. This can lead to severe damage.

In Sweden, a person gets an effective dose of approximately 4 mSv a year. The main contribution is radiation from space, medical examinations and radioactive materials, from the ground and water or within the body. Also, indoor exposure from radon stands for around 2 mSv a year. At MAX-lab, the total average additional effective dose is 0.3 mSv/year. [9]

3.6 Risk analysis theory

At MAX-lab, the MAX IV Laboratory and other similar facilities, it is necessary to have staff constantly working with safety issues since it should be highest priority in order to operate safely. In the long run, if a workplace is considered safe and to be working systematically with safety, it becomes a more attractive place to visit for both users and staff as well as ordinary guests.

Certain terms and words in this report require some basic knowledge about risk analysis. This section will describe some of the terms to further on reading. In order to carry out a risk analysis one has to first identify the potential risks for the specific object that is analyzed. Thereafter, the magnitude of the risks must be evaluated so the right actions are made to efficiently reduce the most severe risks.

3.6.1 Human, technology and organization - HTO

This report will handle the risks from a human, technical and a organizational perspective. This means that by the risks that can occur, it is one or more of these factors that is causing the accident. It can also be indirect dependence when for example a person makes an error but the latent circumstances in the organization is what leads to the accident or incident. For a company, an official or any other workplace, it is very likely a combination of all three when something goes wrong. Therefore, it is very important not to focus on one part but at all three at once. Further on in this report; human, technology and organization will be abbreviated to HTO.

3.6.2 The energy model

The energy model describes how some types of the threats is blocked by a barrier to prevent damaging the target. The threat is described in form of different types of energy, such as electrical energy, mechanical energy, chemical energy or radiation. The barriers are created to isolate the threat from the object it can damage, the so called target and can be anything from a human or an animal to materials or the environment itself. Barriers can be physical like a wall or insulation, but it can also be different types of procedures that must be followed, education or protection in a system that prevents actions made in the wrong sequence are also barriers.

3.6.3 The Reason "Swiss cheese" model

The Swiss cheese model is about hazards making their way through holes or gaps in barriers, see figure 6. These errors can be quite small but since they are many in quantity, they create a path through the barriers which can lead to an accident or hazard. The name refers to slices of Swiss cheese that has big holes in it and where, in this model, hazards can pass. It can often be hard to detect such risks since the deficiency is divided with different barriers. [10]

3.6.4 Plan, Do, Check, Act - The PDCA cycle

The PDCA cycle stands for Plan, Do, Check, Act. It is an iterative looped method that goes on continuously and never ends. The first step is planning to increase safety, what shall be made and what shall be accomplished. In the next step, the plan is implemented and the process is executed. Under check, the results of what have been made is examined to see which efforts that have had an effect and those who haven't or can be improved. If so, this is also the time to find out how to improve the measures that have been made to be able to implement those improvements in the last step called act. This process is then repeated to continuously be able to improve the safety and never feel totally satisfied with the result, since there is always more to do during the next cycle. Especially since the organization itself may be reduced or expanded during time. Also, outer factors like new technology which can be implemented in the organization regarding safety makes it worth to redo the cycle. [12]

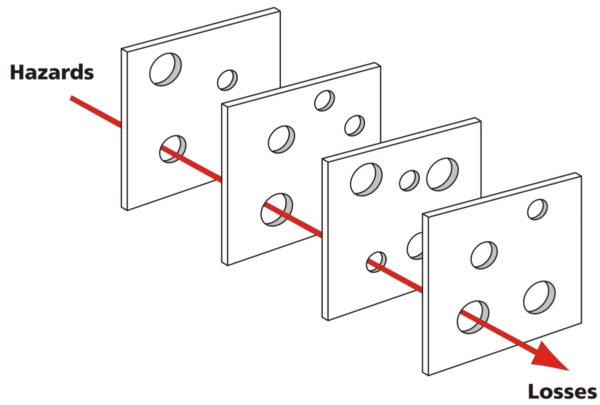

Figure 6: An illustration over the Swiss cheese model. [11]

3.6.5 The Bowtie Method

The Bowtie Method is a diagram which illustrates how a ”top event” and a hazards is caused and what type of outcome it can have. The top event is the main event of the bowtie model and is often the moment when something gets uncontrollable i.e. an explosion of a pressure vessel, someone slips on a roof and falls down or two car collides. The hazard is something that can cause damage if something goes wrong. To the top events described, the hazards can be storing high pressure gas vessel, working on a roof and driving a car. The top event should be carefully chosen but isn't necessary decided directly and depends on what threats and consequences identified. Threats is what causes the top event and can be of different types yet still lead to the same hazard. Threats can in the same order be heat increasing the pressure, slippery roof and to dodge an animal. They are therefore placed before the top event. Consequences are the potential outcomes of the top event and can be sever damage on nearby buildings, a broken leg and a damaged car. Consequences are then placed after the top event. The name bowtie method is referring to that it look like a bowtie when the model is complete, see figure 7. [13]

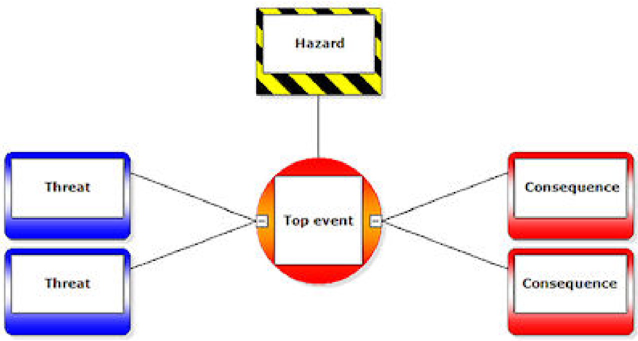

Figure 7: An illustration over the bowtie method. [14]

3.6.6 The SRK framework

To describe how much effort it takes for a person for different types of psychological processes, it is possible to speak about the SRK framework. SRK stands for skills, rules and knowledge and is within these levels where the processes are distributed. The framework/model was developed by Jens Rasmussen and is referred to as "Rasmussen's SRK model". [15]

The three levels are described as:

- Skill-based level: At the skill-based level, very little conscious control or focus is needed to perform a task. This process is often made completely automatic and makes it possible to concentrate on other things at the same time. An example is to ride a bicycle.
- Rule-based level: At the rule-based level, there are already rules to follow for a specific task. This means that no certain knowledge or insight of how it works is needed as long as the rules are followed. This can be an algorithm where things are thought to be in a specific order like an construction manual and there is no need to know why it should be assembled in a specific way.
- Knowledge-based level: The knowledge-based level describes the processes that requires large focus and where it is needed have a greater knowledge and understanding of the principles and laws within the system in order to fulfill a task. This level is reached when something unexpected occurs or when improvements and inventions of and in a system are made.

4 Parts, systems and processes at the MAX IV Laboratory

4.1 Radiation protection

Radiation at synchrotron facilities is considered a great concern. The major part of the radiation comes from the linac and the storage rings, but also from the beamlines. The radiation diverges both radially from the beam and in its current longitudinal direction. However, once the beam stops, the radiation disappears immediately. In the linac and the storage rings, most of the radiation comes from so called "bremsstrahlung" in form of gamma radiation. This happens when electrons falls out of its equilibrium orbit and decelerate in the surrounding matter. In the exp. hutch, only X-ray radiation is present since these wavelengths are filtered out from the synchrotron radiation. For most countries, laws and regulations are enacted specially for accelerators. The laws and regulations regarding the synchrotrons at MAX IV Laboratory are written by the Swedish Radiation Safety Authority. Especially regulation 2008:27 regarding operations with accelerators, and regulation 2008:51 concerning basic provisions for the protection of workers and the general public in practices involving ionizing radiation.

At the MAX IV Laboratory, numerous of actions have been taken to reduce the amount of radiation where staff and visitors are present during operation. Regarding the beamlines, their designs are quite different from each other, but are still bound to the same restrictions and regulations regarding radiation protection.

Both MAX IV and MAX-lab are divided into three sections; normal areas, protected areas and controlled areas. The unprotected areas are areas where no specific training or safety equipment is needed. One may still need access to these areas (see 4.5) but is safe from radiation and other potential risks not included in an ordinary office building. The main normal area at MAX IV is the main office building. Protected areas are areas like the main experimental hall and the hall for the second ring. This hall will be expanded to also contain some offices meaning they will belong to the protected areas as well. All persons who are working in protected areas must undergo the safety course (see 4.2) and eventual other courses depending on the type of work. Controlled areas are at both MAX IV and MAX-lab the linac tunnel, the two storage rings and the beamline hutches including both the experimental and the optical. All the beamline hutches at MAX IV are coated in orange to visually distinguish them from the other protected or non-protected areas. This is done in order to prevent anyone from attempts of entering those areas while the beam, and thereby synchrotron radiation, is present. If so, the beam would directly shut down because of the PSS (see section 4.3). The radiation protection of the hutches is also improved compared to MAX-lab by using so called chicanes for all cables and pipes leading in and out from the hutch. The chicanes prevent radially emitted light leak out from the hutch compared to cable holes going straight through the hutch walls, see figure 8.

Figure 8: The inside wall of the hutch facing the storage ring. The figure shows the incoming pipes for the gas system from the cabinets outside. To the right, a chicane without its cover is shown.

4.2 The safety course

Everyone who will work at the MAX IV Laboratory with the exception of those who work in the main office building have to undergo a safety course. At current

MAX-lab, the safety course consists of a twenty minute lecture with mandatory knowledge regarding safety, custom made for MAX-lab. Some of the major categories in the safety course are:

- Fire safety
- Measures in case of accidents
- Radiation: Area types and signals/signs
- Chemical treatment

This course will be revised for MAX IV and is currently under development. It will probably contain a quite similar content with some improvements and adaptions. It will be a web-based course with a basic block and additional types of sections depending on what purpose of work or research for visiting the facility. After the course is finished, it is necessary signing on in order to be approved for work or research.

The new safety courses for guest scientists, staff and co workers at MAX IV will be web-based and performed in MAX IV U (see section 4.4) consisting of different blocks depending on what type of competence that is needed for specific types of work. For example, to use an overhead crane (not for ordinary users) a person must undergo a special safety course for operating them. For users, the safety course will be carried out after or during the visit registration in pre-beamtime phase, see section 4.12. There will probably be three levels of competence depending on which locations at the site the person need to access where guest scientists will require the lowest access level. The idea is also to adapt the safety course for the different beamlines, i.e. all scientists will have to go through specific parts in the safety course which handles the safety aspect at the beamline on which experiments will be carried out. If the users intend to operate in the chemistry lab as well, an additional part of the safety course (still at lowest level) is required. There is also practical instructions for users by the beamline staff, further described in section 4.12.

4.3 PSS - The Personal Safety System

The Personal Safety System PSS is a system developed in order for the staff, users and visitors to work and visit the MAX IV Laboratory safely. A safety system like this isn't anything unique and similar systems exist in some extent at most types of industrial facilities over the world. However, the configurations of the systems must always be adapted and regarding the MAX IV Laboratory, it can be considered very complex and unique due to the high potential risks within the facilities. The PSS can include accessibility for doors and gates, monitoring and searching areas and safety procedures to follow in order to perform a task. In general, it can include every system that has to do with increasing personal safety. At the MAX IV Laboratory, the PSS is most often referred to the search procedure in order to start or open the beam in controlled areas. The PSS is described in further detail for the hutches of I811 and Balder in the next sections.

4.3.1 PSS at the I811

When the experimental setup is complete, there is a small procedure also under the PSS to be able to start the experiment. First, one makes sure that no one is left behind in the exp. room. This is also made as a procedure where a button called "Start search" is pressed on the control panel. Thereafter a person has twenty seconds to take the key, go across the exp. room (around 8 meters) to insert and turn the key in another lock. Then take the key back to the control panel and press "Search complete". When "Start search" is pressed, a siren and a warning light is activated for about thirty seconds. This system is made to force a person to go across the room and control that no one is left behind. Then, the door can be closed and the key can be turned on allowing the beam stopper to open.

Considering this procedure from a HTO perspective, it is seen how the system lays the responsibility for a safe experiment somewhere between humans and technology. The safety measure forces a person to follow the right sequence in order to operate the main system which in this case is the beamline. As mentioned before, it's preferable to blame the system when a person eventually makes an error that can cause an accident. If the system is "fail-safe", then no accident will happen no matter what sequence is used to perform a task. One can argue if this system at the I811 is fail-safe or not. Persons are forced to start the beam to a specific algorithm or the beam stopper will not move away and the experiment can't be carried out. It is fail-safe in that regard that one is forced to move across the room in order to search for people left behind before you close the door. However, it is not a complete fail-safe system since you only force a person to go across the room, but he or she aren't obliged to specifically search for anyone as it is designed today. The key switch is placed on the wall which doesn't contribute to the search since focus should be in the opposite direction. The walking path during the search don't cover the whole room even if its quite small, especially the floor behind the experiment table. The process is often repeated numerous times a day for every sample that is tested. Some guest scientists say that the procedure becomes a routine in which you don't necessary search for persons left behind, and only go through the procedure because it is necessary in order to start the experiment. The twenty second time limit can also encourage to be quick and inattentive while searching. However, as mentioned the room is relatively small for a person to be missing and even so, the radiation doses are reasonable small and it will probably not be long before a missing person is found. It is also rarely more than three or four people in the exp. room at the same time. Still, if the search sequence becomes mechanistic and no actual search is made during the process, then perhaps this PSS search has room for improvement.

4.3.2 PSS at BALDER

The PSS at BALDER will look quite different from the one at the I811. As seen in figure 9, BALDER will have four buttons for the search sequence within the hutch that need to be pressed in the right order. Compared to the I811, the Initiate search button (the green dot) is placed inside the hutch instead of outside. Also, a time delay is implied making sure the buttons aren't pressed too fast so the search becomes less carelessly made. Compared to the I811, there is instead a maximum time which limits the search time. BALDER will also have a search time limit, but it will be set so the person who is performing the search shouldn't feel any stress finishing the search in time. The time limit is mainly to make sure that the search is made in one sequence and not interrupted in between. The exact timescale for the different parts of the search sequence isn't determined yet, but the minimum time between pressing the search buttons will probably be around 10 to 30 seconds. The PSS at MAX IV will have two independent parallel systems to make sure that if one of the systems fails, there is always an extra system operational. At BALDER, it will be possible to mount multiple samples at one time unlike the I811. This will reduce the amount of times the users have to go in the hutch to change samples and to run the search sequence. The optics hutch for BALDER as well as all other hutches along with the linac and storage rings will also have their own PSS. Since BALDER users normally aren't allowed in the optics hutch or the other controlled areas without authorized personnel, this part is less relevant for this report. The safety staff has the responsibility for the PSS at the MAX IV Laboratory.

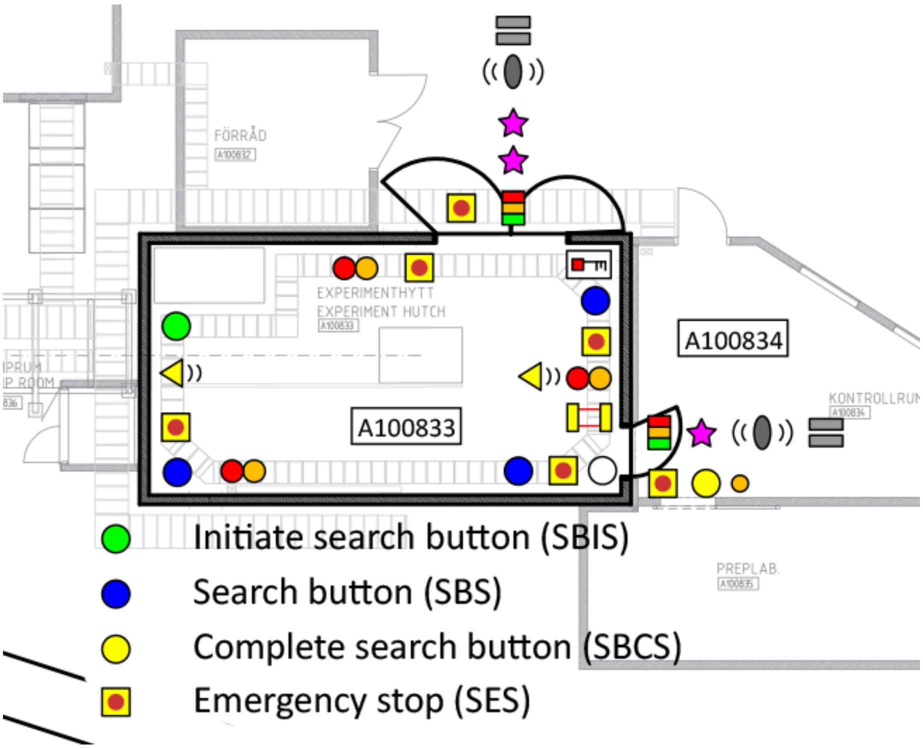

Figure 9: The PSS at the BALDER exp. hutch. Starting with the initiate search button, the searcher goes clockwise according to the figure and press the other search buttons in that same order. After the last search button is pressed, the searcher leaves the hutch to enter the control room and shut the door. At last, the complete search button outside the hutch is pressed in order to finish the search sequence. Note that the PSS include four emergency stop buttons within the hutch as well.[18]

4.4 MAX IV U - A digital user interface

The digital user interface - MAX IV U is a web-based software to facilitate for both staff and users at the MAX IV Laboratory. The purpose is to enable people of working wherever they are and not forced to specific locations. For the users, this makes it easier for them to send in proposals and taking care of pre visit duties (see section 4.12). If their proposals are accepted, all users must individually register their visit in MAX IV U. Here is also where they undergo the mandatory web safety course.

4.5 RCO and SALTO - safety lock systems

Two different systems for accessing the around 500 doors will be used at MAX IV. These are called RCO and SALTO which also are the names of the companies delivering the systems. The main difference between these systems as they are made for MAX IV, is that the RCO connected doors are constantly online and communicating with a terminal where the accessibility for users is controlled. The SALTO system however, is an offline system which gets information about accessibility and passages by the users own tags. The information within each tag is updated daily when it's used in one of the main connected devices. The RCO system will be connected to the main doors entering the building and to some of the more critical doors regarding personal safety, such as the doors to the storage ring and the linac. The SALTO system will mainly be used inside the building on doors which doesn't lead to radiation protected or other safety areas.

4.6 The beamline I811 at MAX-lab

Since BALDER, at the time of writing only exist in planning stage, it is hard to make a proper risks analysis of the object. However, the current beamline I811 is one of ten connected to MAX II and is considered to be quite similar to BALDER. This makes it possible in some extent to analyze I811 in able to see what types of risks there are today and what has been made to reduce them. Also, to understand how the process of research is carried out by the guest scientists and co workers at and around the beamline. EXAFS and XANES are also the methods used at I811 which makes the equipment and the environment similar to how BALDER will be. Certain experiment methods such as diffraction spectroscopy is also used at the I811, but since it won't be used at BALDER, it is not further analyzed in the report.

I811 consist of the beamline itself that leads in to the experiment hutch. There is also an adjacent control room to the hutch where the beamline is controlled and results are analyzed. In order to enter the exp. hutch in which may contain radiation, one has to first open the door with a key which must be inserted during experiments. The key is placed right outside the door on a control panel. When the key is turned off, there is an automatic beam stop made of thick lead that prevents the beam from entering the currently safe exp. room. If someone tries to open the door by force, the whole ring of MAX II is shut down which thereby also affect the other users of MAX II beamlines. This can be seen as a fail safe system and is a part of the Personal Safety System (PSS) where the combination of humans and technology is used to prevent anyone from entering the room during an experiment.

There are other safety measures at I811 and most, if not all, will be implemented at BALDER as well. Since they are already taken into consideration, this report will only mention them briefly in the list below and only discuss them if room for improvement is found.

- Oxygen and carbon monoxide detectors in the exp. hutch to detect low oxygen levels or high poisonous gas levels.
- An overhead crane to facilitate heavy lifts.
- Overall lead protection with lead covered windows to prevent radiation leakage from the exp. hutch.

4.7 The floor plan of BALDER

The beamline BALDER itself consist of, except for the optics hutch, the prep. lab, the control room, the exp. hutch and a storage room as can be seen in figure 10. There will also be a type of workshop somewhat right to the storage room in the figure.

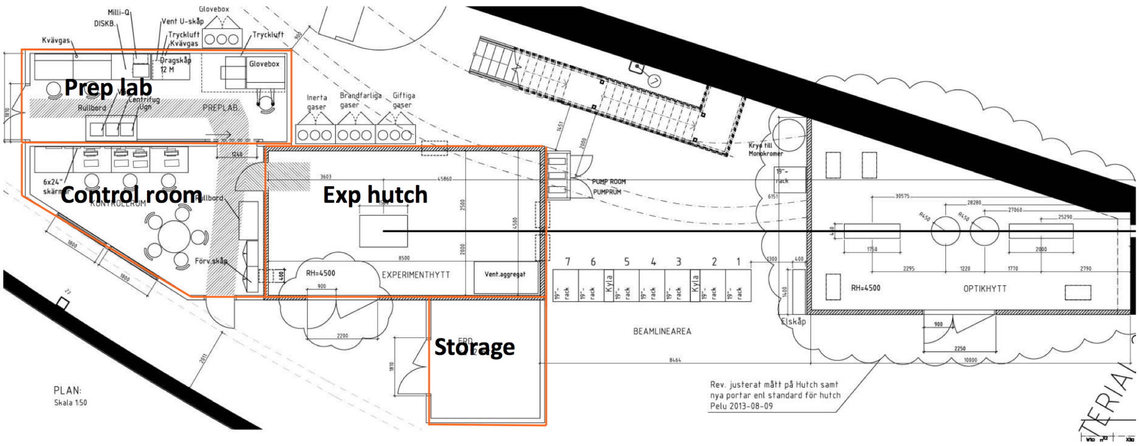

Figure 10: The floor plan of BALDER.

Since the construction of BALDER is made, it will probably be difficult to implement changes to the things mentioned in this section regarding the floor plan. The floor plans are also more or less different from each beamline which means that parts in this section may already be dealt with at other parts of MAX IV. The two main reasons why they are different is because they are all planned by different teams and have different purposes. However, eventually this section may be taking into consideration when developing new beamlines in the future.

- The door for entering the exp. hutch in between experiments is connected to the control room. Even if the prep. lab is adjacent to the beamline itself compared to the situation for I811, it is now necessary to transport samples from the prep. lab to the hutch via the control room. This will probably not be of any direct danger since the majority of the samples are harmless, and it will only pass a fraction of the control room in the top right corner. It can however still be seen as unnecessary, especially if the sample is constituting a risk, since there is no direct purpose of having a sample in the control room at any time. However, the downside of instead having it connected directly to the prep. lab is that a person entering the hutch must go by the prep. lab as well. In the design of I811, it may have been the better solution since only one sample can be analyzed at a time and has to be changed manually in between. This means that persons entering the hutch have to enter the prep. lab to fetch samples almost every time anyway. At BALDER however, numerous of samples can be analyzed automatically meaning that scientists have to enter the hutch significantly less, as low as two times; first to place the samples and then to get the samples after the experiment. At the I811, every additional sample means entering the hutch at least one time more.

  The solution could be two doors into the hutch (except from the gate that only is used when moving bigger equipment) one from the control room and one from the prep. lab. This causes however other issues such as a higher risk of anyone entering the room from one door when another thinks it is empty. It will also require a more complex PSS and of course an extra door, which leads to higher costs. The consequences for two doors are in short probably higher than the gain.

  Another thing to consider, since one of the purposes of the floor plan is to reduce unnecessary visits in the prep. lab, is whether the door from the main hall to the prep. lab should be accessible at all times or not. If it is, no samples to the prep. lab have to go via the door from the main hall to the control room. On the other hand, it may be used as the regular door when entering BALDER which may not be the main purpose.

- Secondly, the control room is placed directly in the longitudinal beam direction. Since the control room is where the guest scientists spend most of their time during experiments, it can lead to unnecessary exposure of radiation. But as mentioned before, the exp. hutch is a radiation protected area and the walls are constructed to prevent radiation leakage at any direction. The wall between the hutch and the control room is also enhanced with a thickness of 12 mm led instead of the otherwise 7 mm at the sides and 6 mm in the roof [16].

- The top right corner of the prep. lab (see figure 10) reduces the visibility on the outside. Accidents can for example occur when someone is about to deliver gas cylinders with a truck to BALDER when a person who has adjusted the gas flow on the outside is about to go back inside to one of the rooms. Since the nearest door in, is to the prep. lab, the chances are that a collision and thereby an accident may take place. It should be noted that since the gas system will be controlled from the control room (see section 4.8), the users themselves have no purpose of being near the gas cylinders at any time.

4.8 The gas system at BALDER

BALDER will have a quite complex system for providing gas to the experiments into the hutch. Only a few beamlines at MAX IV will have the opportunity to work with gases in their experiments and only BALDER will have the possibility to obtain as high pressures as up to 50 bar. The gas handling is one of the major concerns at BALDER and a lot of improvements has been made compared to the I811 and MAX-lab in general:

- The gas cylinders are now located outside the hutch instead, except for the user gas cabinet nr. 5. They are also placed inside 30 minutes fire proof gas cabinets for extra protection. This seals off most of the gas from the enclosure of the hutch. There will be a possibility for bringing own special gases by the guest scientists themselves, they are however most likely to be placed inside cabinet nr. 5 in the hutch but it is not finally decided.

- The gas system is further developed. Except for the chicanes to prevent radiation leakage, the pipes and equipment to connect the gas cylinders are made to increase compatibility so that guest scientist don't have to bring their own systems. This insures an extra control over quality and management of the system to the staff compared to today.

- All gas cylinders used at BALDER and the rest of the gas demanding beamlines will be distributed from MAX IV's own intake in order to have control over which gases that are present in the facility.

- Major technical improvements will let the users control, mix and monitor gases and gas flow from the computers in the control room, no manual adjustments on vents and cranes is necessary.

There will be five gas cabinets connected to BALDER; The first contains inert gases such as helium, argon and nitrogen gas. Cabinets 2 and 3 will contain flammable gases as hydrogen gas and carbon monoxide. Cabinet nr. 4 will contain inert but oxygen reducing gases and nr. 5 is, as mentioned, for user supplies. All the cabinets are made for standard cylinders of 50 liters with a 200 bar pressure, every cabinet will have room for 2-3 cylinders.

How the exhaust system and the pressure valves will be designed isn't fully decided yet. However, it will have manometers after every regulator to detect that the pressure isn't exceeding the limit of 50 bar (200 bar cylinders will be used at the primary side before the regulator). Cabinets nr. 2 and 3 (flammable) are equipped with special pressure vents in order to prevent any leakage or damage on the secondary side after the regulator. There will also be detectors and controllers for the gas flow. In the hutch at about eyesight, different gas detectors are to assure that no dangerous gases are leaking. There will at least be specific detectors for hydrogen gas, carbon monoxide, oxygen and one for detecting gases containing sulfur.

For inert and the majority of the gases, leakage isn't a major concern. The biggest gas cylinders are 50 liters at a maximum of 200 bar pressure, which would give 10 m^3 volume of gas. Compared to the exp. hutch volume which is almost 173 m^3 [16] making the volume only reducing the normal air by 5.8 %. However, for toxic and flammable gases, a gas leakage is far more dangerous. At some times liquid nitrogen is used contained in a 200 liters tank within the hutch. A leak will make the nitrogen go to gas phase and expand 682 times [17], implying that the tank has a potential of around 137 m^3 nitrogen gas which could fill around 80 % of the hutch. Nitrogen gas is also almost as heavy as oxygen making it rise slowly towards the ceiling. Even if the two gases are entirely separated, there will only be oxygen up to around 85 cm above the ground. The gas will however most likely be ventilated quite fast via the ventilation system.

4.9 Chemistry lab

The chemistry labs are available for all the users at MAX IV who have taken the safety course regarding the chemistry labs. This means that they don't belong to any specific beamline and are placed with access from the main hall. The chemistry labs can be used for different chemistry purposes such as dealing with toxic or other dangerous substances. It can also be used to prepare ordinary samples in one of the fume cupboards. Since the prep. lab at BALDER also have a fume cupboard, the chemistry lab may not be used so frequently by BALDER users.

4.10 Electricity

MAX IV will have an power consumption of 5 MW (källa) which corresponds to a few percent of the total power consumption of Lund. Most of the electricity at MAX IV will be used for the linac and the storage rings, but the beamlines will also be equipped with a lot of power consuming electrical hardware such as computers, measuring devices and sensors, regulation systems, PSS, pumps, lights, lasers (not at BALDER), overhead cranes and ovens. Because of the radiation in the hutch, electronic equipment may be damaged, therefore as much hardware as possible is placed outside. It will most likely be placed somewhere between the two hutches (the experimental and the optics hutch). However, there are still many components as the measuring devices for the experiments that need to be close to the sample, in order to achieve a high signal-to-noise ratio. This means that the hutch will still be a very high density environment of electronic equipment.

All electricity and electrical equipment involves some sort of risks, the direct risk is of course for a person to get a shock. However, all fixed installations at MAX IV are made by authorized personnel. This means it shouldn't be a noticeable higher risks than at other facilities with the same comparable amount of electronic devices. Since users neither are allowed to bring their own electrical equipment without permission nor work with damaged equipment, they shouldn't normally be exposed to these risks as the electricians themselves are. Even so, they are still obliged to take the necessary precautions in order to operate safely. This may be when the human factor is noticeable, if something isn't working properly, users may try to correct it themselves and might get a shock as a consequence.

The electricity can also get indirect consequences, for example starting a fire. Especially if too many cables are placed together, which could be considered most likely at some places in MAX IV because of the comprising number of cables. The number of cables can also lead to persons falling if they aren't properly placed. At MAX IV, cable ladders are mounted in the hutch over 2 meters above the ground and on the walls. This reduces the amount of cables at the floor or in the space area where staff and scientists normally operate. The overhead crane is placed over the cable ladders to prevent cables going vertically down to the experiment table from getting damaged by the crane. This is however still a possible scenario when the overhead crane is moving objects. There will also be fixed installations at the experiment table where different devices can be connected instead of needing to draw cables over the floor.

4.11 Accidents and incidents at MAX-lab

In order to evaluate the risks, it might be a good idea to examine similar objects as a reference of what types of accidents and incidents that can occur at the new site. MAX-lab itself can be considered a very good reference since both laboratories are constructed by the same principles. Most of the staff will also come along to the new facility which in some extent mean the same kind of reasoning regarding safety. This implies to similar safety measures and risks prioritizing and at the end it may in some extent lead to similar accidents and incidents from both happening and being prevented.

It is somewhat problematic to look at previous accidents and incidents at MAX-lab since the documentation, especially for the first half of its almost 30 years running, is fairly insufficient. The incident reporting has however increased and has been improved during the years. From the documentation it is possible to read about the accidents happening from 2000 until today.

- A small H_2S gas leak due to a broken regulator in 2002, where a user opened the gas cylinder even when already expecting a gas leak by the smell.
- Another toxic, flammable and corrosive gas leak occurred with methylamine CH_3NH_2 in 2005. A small cloud of gas emerged when the cylinder was opened and a smell of ammonia aroused due to a bad rubber hose.
- Regulators on gas cylinders without gaskets, luckily on cylinders containing inert gases.
- Some incidents have occurred in the chemistry lab where hydrogen fluoride HF has been placed non-sealed in a locker, and where acetone has been confused with water.
- Two scientists exposed to beryllium Be from a broken detector in 2014.
- A serious laser accident 2008 where the injured had taken off his safety goggles during an alignment. Lasers don't exists at BALDER so they won't be a threat for these users.

- A scientist and his son was exposed to radiation while being inside the nuclear facility experiment station while the beam was running due to a misunderstanding. The maximal dose of exposure was considered less or equal to a dental radiography (typically 5 to 10 μSv [22]). This event isn't documented and therefore undated.

Along with these accidents and incidents at MAX-lab are numerous of small fires and staff getting electrified. Also numerous of minor injuries while working with tools and machines. Many accidents and incidents have probably not been reported during the years. This reason could be that no one has had a clear assignment of handling incident reports or simply that persons don't feel the need of reporting minor injuries.

4.12 User visiting process

In order to understand what risks the guest scientists (users) may encounter, it is necessary to consider the phases and steps that are undertaken within the whole user process. This is shown in figure 11 where the different phases are categorized in chronological order with underlying steps within each phase.

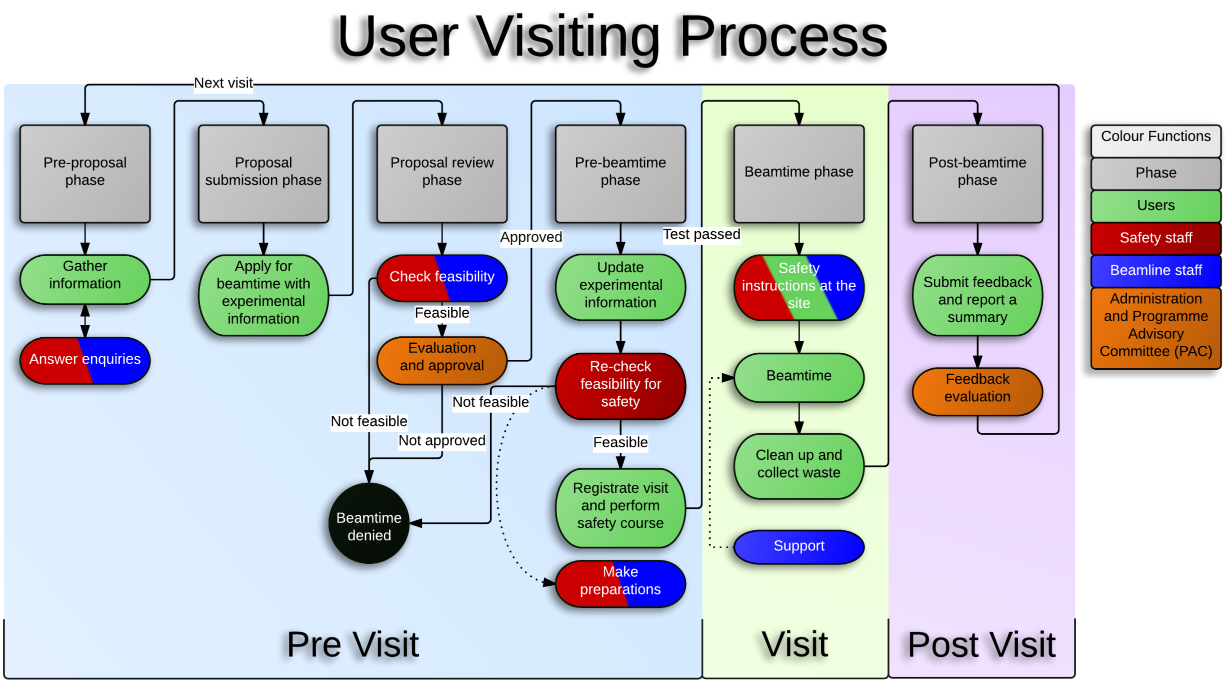

Figure 11: An illustration over the steps and phases within the user process. Note that this is a simplified illustration and only shows the basic concepts. Normally many of the steps happen simultaneously and information is shared during the whole process.

- Pre-proposal phase: Here is where the first contact the MAX IV Laboratory is made. The proposal creator gather information from the beamline staff and sometimes from the safety staff as well depending on the experiment. Usually scientist already have a good knowledge of which method to use in order to carry out the experiment. They also often know what type of equipment they need during the beamtime and if they require materials that may be increasing the risk of the experiment. If so, this is where the safety staff needs to be informed.

- Proposal submission phase: Now it is time to send in the proposal, including information about what type of experiment and what they might need. At BALDER and the other beamlines that manage gases and chemicals, information about which types required in the experiment must also be presented in the proposal. They also propose desired dates to experiment and for how long they want to stay and how many they are. Usually they are between two and four persons, but for some shorter experiments, around a 16 hour shift, they can be alone as well.

- Proposal review phase: In this stage, the formal proposal is up for inspection, and is controlled by the beamline and safety staff to make sure that the experiment is feasible. The beamline check consists for example if the experiment itself actually can be carried out at that specific beamline or perhaps if another beamline with another experimental setup and method is better. At specific experiments, the safety staff mostly focus on if unconventional methods will be used or equipment and special gases should be brought in. If so, this has to be investigated further to be sure that the experiment can be carried out in a considerable safe way. Both the beamline staff and the safety staff have to approve to the proposal. If not, then the proposal is denied. Otherwise it passes through to the Programme Advisory Committee (PAC) for a final approval. PAC is the division where all experiments are brought in for the last permission step and they also decides which experiments that will be carried out. All the approved experiments are then distributed to the beamlines for scheduling. Note that the person writing the proposal isn't necessary one of the persons who actually perform the experiments at the site and is not necessarily considered a user.

- Pre-beamtime phase: If the proposal is approved, the next step is for the user to register their visit and update information in MAX IV U, see section 4.4. The registration is required for every user at the MAX IV Laboratory. At this stage, it is also necessary to perform the online safety course which is described further in section 4.2. The safety course is mandatory to pass for all of the users in order to carry out the experiment. If it isn't read and signed before the visit, it must be made on site before entering the protected and controlled areas. At the same time, another safety check is made to be fully certain that the experiment once again is considered feasible.

- Beamtime phase: This is the main stage, both for the process itself and for this report, since this is the only stage where users actually visit the site. Therefore it will be described further in section 4.12.1 together with figure 12.

- Post-beamtime phase: After the visit and the users have returned home, they are obliged to write a small report of their experiments of what they have done and what their conclusion is. They also need to submit feedback regarding their pre visit phases and especially the visit (beamtime) phase.

4.12.1 Beamtime phase

The usual duration of the beamtime phase is often half a day to a couple of days for the hard X-ray beamlines, and one to two weeks for the soft X-ray beamlines. This is due to the baking process and vacuum pumping that consumes very much of the beamtime for the soft X-ray beamlines. At BALDER, which uses hard X-rays, this isn't any bigger problem. When the users arrive to the MAX IV Laboratory, which can be any day of the week, they are required to contact a person from the beamline staff of the specific beamline they are about to use, often passed on by the administration. The staff member then guides the users to the specific beamline where at least one is given practical information in safety and how to operate the beamline in general on site. Regarding safety, the PSS (see section 4.3) is demonstrated and explained. Also, where to go during an emergency evacuation and measures in case of an accident. He or she has then the responsibility to inform the rest of the users in the team. This is usually made on normal weekdays when most of the staff is working but can also be carried out during weekends if any beamline staff is available. Note that without this introduction to the beamline, no user is allowed to start experiment. If the safety staff also needs to get involved, then this introduction always takes place at normal weekdays. Other information regarding safety can be how to turn on or connect gas containers to the system, using the head crane (a special education mandatory and should normally not be carried out by users) or to use the prep. lab. Much of the information is also about how the software interface is used and how the beam and the gas system is controlled from the computers.

There is however no strict regulations or guidelines today of what happens if the user who was given the practical safety instructions leaves before the experiment is carried through. Today, this information is only passed on to another user by the informed team member, which hasn't the same authority and knowledge as the beamline staff to present this information. This may lead to misunderstandings and information loss along the way. This problem will also occur every time the safety informed user is away from the beamline. On the other hand, there shouldn't be anything at the beamline making a user more vulnerable and exposed to danger if they only have taken the web safety course. If this is seen as a concern, the direct solution is demanding every user to get instructed directly by the beamline staff as well, which may increase their workload.

When the users has completed the introduction of the beamline, they are ready for the start-up. The start-up includes steps like preparing samples in the prep. lab or in the chemistry lab. At MAX-lab, most of the preparations should be made in the chemistry lab since there is no prep. lab adjacent to the I811. But

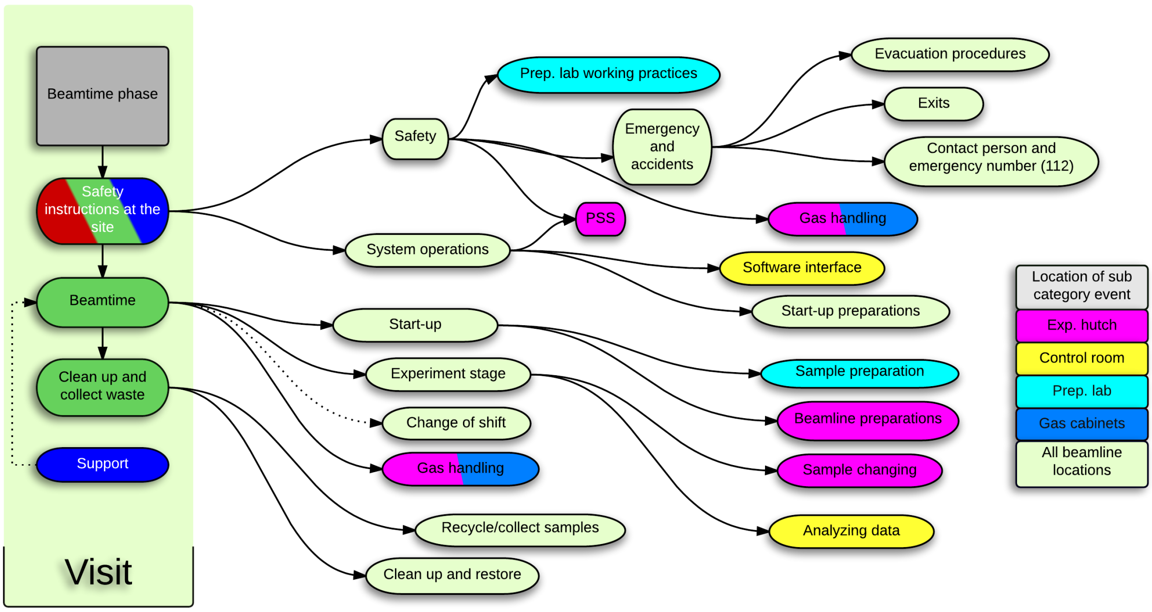

Figure 12: The beamtime phase illustrated in further detail with some of the sub categories in which the beamtime phase holds. The background colors describe in which location within the beamline where the event is taking place.

since it can be quite far to the chemistry lab, some sample preparations are made in the control room instead. At BALDER, there is, as shown in figure 10, a prep. lab adjacent to the beamline itself. In the prep. lab, there will be an oven, a fume cupboard and a glove box. The glove box will have an inert argon environment in order to prevent impurities at the sample. The samples are often not more than a couple of grams and the concentrations of the desired substance can be as low as down to ppm. The samples often contains of a small brick. The brick has a hole where the substance is filled and sealed with lead free tape (to not interfere with the core electron interactions). However, many different samples are used depending on what type and in what physical state it is, meaning the gas itself can be the sample. Preparations usually take a couple of minutes per sample. This can however take several hours depending on the number of samples and if it's a critical mixture process with exact concentrations or masses. Preparations must also be made with the beamline itself since different experiment require different experimental setups. At BALDER, some experiments requires samples contained in a gas chamber and some do not require any containment at all. Different experiments also require different types of gas mixtures with different kinds of pressure. This is made in order to both detect how the gas reacts with the sample, or to prevent it to react at all and to prevent any other substance from interfere with the collected data. Depending on the thickness of the sample, the absorption is measured either direct with a detector behind the sample, or indirect using fluorescence with a detector around 45° angle in front of the sample. The preparations of the experimental setup can often require a couple of hours. It can also take as little as no time if all settings are as for the previous experiment. At the I811, using diffraction spectroscopy will most likely require the most amount of work in order to prepare, and it can take up to a couple of days including the alignment of the beam. Since this method isn't used at BALDER, this will no longer be a problem. At MAX-lab, there is no beamtime for any users at Mondays since this time is reserved for maintenance of the synchrotron. This becomes a good time for new users with long start-ups to prepare their experiments. There will be something similar at MAX IV, but how the periods for maintenance will be scheduled isn't decided yet.

After the preparations, it is time to mount the samples, do the PSS search sequence (see 4.3) and open the beam stopper to start the experiment. At BALDER, there will be a rotating plate with multiple samples. This makes the beamtime more efficient since it reduces the number of times users needs to enter the hutch and change samples. To mount or change samples usually take a couple of minutes at the I811. At BALDER, it is harder to tell because of the multi sample rotating disc. There will most likely be several discs to rotate between so one of them always is irradiated in the hutch. The samples are only in the magnitude of grams, meaning the holder of the disc mechanism doesn't need to be fixed so hard and probably is changed in the order of minutes as well. Regarding gas samples, it is more a question of mixing different types with different concentrations. This can be made from the control room meaning no extra visits to the exp. hutch in this case as well.

During experiments, the users may prepare other samples or subsequently analyze incoming data or work at something else on their computers. In between, it also may be needed to do gas mixtures or to change empty gas containers. This regards mainly the eventual own brought gases in gas cabinet nr. 5 (see section 4.8) since the other cabinets most likely will be supplied by the main staff. Otherwise the actual experiment stage is, if everything works as it suppose to, mainly about waiting.

During the waiting time there are some non work related things to do such as go to the gym in the basement of the main office building. There is also a possibility to cook or prepare food in the coffee room/kitchen also in the main office building. Usually the scientists work in shifts to monitor the experiments which can take several hours at a time, especially with a rotating disc technique for the samples. Note that if hazardous gases (toxic, flammable, radioactive etc.) is used, then they will need at least one person to monitor the experiment due to prevent unexpected events or accidents.

When the beamtime is about to finish, the users clean up and collect or throws away their waste. Usually, the waste is harmless and can be recycled as any other waste. If it is considered harmful, the handling process is dealt with in the pre-beamtime phase together with the safety staff.

To be a user at sciences facilities like the MAX IV Laboratory can be quite different from what scientists are used to at their regular working places. Some may only visit the laboratory one time in their life and the preparations can be months. For this reason, they may feel stressed during the visit, especially if everything isn't working properly. This may also lead to longer and more exhausting working days than expected, which may lead to irrational thinking. Therefore it is very important that the safety systems are as fail-safe and simple as possible. The beamtime phase doesn't require so many decisions under a long period of time as well, this will probably also affect awareness and may reduce the alertness of the users.

5 Analysis

The process for a user during a visit has been described in section 4.12. A user is spending most time during work time in the prep. lab, the beamline control room, the exp. hutch and possibly the chemistry lab. The different identified risks are shown in figure 13 where the different percentages describes roughly how much time spent at each location. It should be noted that these percentages are only a typical example of an "ordinary" visit. The times can vary drastically, especially for a large user team with different assignments. Some of them may for example sit in the prep. lab or chemistry lab the entire beamtime, in order to provide prepared samples for the rest of the team to mount and examine. Sometimes, the experimental setup has to be reconstructed to fit the users specific demands and sometimes it is properly adjusted right from the beginning. It can also be something wrong somewhere at the beamline path that takes time to adjust or repair, meaning the percentage of time spent at each location can vary vastly. It also depend on the duration of the visit, these percentages are based on a beamtime of 24-48 hours.

The figure shows the different identified risks for the different locations. As can be seen, some of the locations have more risks than others and some categories of risks are more represented than others. However, it doesn't say anything about the magnitude of the risks other than that it may be present.

5.1 Radiation

Regarding radiation, there are relatively few risks at most experimental locations. Except for radioactive materials and samples, most of the risks regarding radiation are only present in the hutch during beamtime. Furthermore, radioactive samples are very rare, and they are treated with extra care and precautions. The amounts are also often very low since experiments at BALDER require less than a gram. The radiation in the hutch (X-ray radiation) is fairly low. To be locked in for an hour while the beam is running may increase the probability for cancer in the next decades, but the amount won't kill or harm anyone directly. For beamline staff and frequently returning users this may however be fatal if repeated and put into routine. The radiation is of course a risk and should be avoided as much as possible at all times. The risk of radiation however, is much larger at other parts of the facility such as the linac and the storage rings. The optics hutch is also much more dangerous to be left inside than the exp. hutch due to radiation since only a few percent of the beam intensity leaves the optics hutch. The optics hutch is not a concern for ordinary users.

	Radiation	Gases and Chemicals	Fire	Electricity	Miscellaneous
Prep. lab 10-20%	Low	Low	Oven	Low	Burns
Control room 70-80%	Low	None	Computers Furniture	Computers	Tiredness
Exp.hutch 10-20%	Synchrotron radiation	Gas system Cabinet nr. 5 Liquid nitrogen Pressure	Hardware Cables Gas Oven	Hardware Overhead crane	Sample robot Tiredness Gets knocked by object, slips or gets ill Overhead crane
Chemistry lab. 0-10%	Radioactive materials	Toxic Flammable Radioactive Corrosive Substances	Flammable Chemicals and gases	Low	Slips or gets ill

Figure 13: Risks for users at BALDER shown in a matrix for different types of risks in the different locations, along with an approximate time spent at each location in percent.

5.2 Gases and Chemicals

Gases and chemicals are used frequently, especially at BALDER where they play an important roll. These risks are primarily in the exp. hutch and the chemistry lab, since the argon gas provided to the glove box in the prep. lab is inert and in a small amount. As mentioned in section 4.8, most of the gas will be lead into the hutch from the outside (the main hall) and will be controlled by computers in the control room. The exception will possibly be cabinet nr. 5 if placed inside the hutch. Also, temporary nitrogen tanks in the hutch will represent a risk. Even if the cylinders may contain different substances, as long as they are contained, they are usually not of a concern. Most of the risks regarding gases involves some sort of leakage. A gas leakage inside the hutch will most often not be a problem if they are inert since, as mentioned earlier, they can only fill about 5.8 % of the air space. It can however be a problem with liquid nitrogen because of its expanding volume. Often a leakage is noticeable for example with a sound, vapor or a temperature drop, but it may also be something no one is reacting to. Since a leakage can empty a tank quite fast and relatively quiet an expansion may reduce the oxygen level rapidly, as mentioned up to 80 % of the hutch volume. It may also create frostbites at exposed body parts.

Most of the ordinary gas cylinders themselves are placed outside the hutch in gas cabinets, and a leakage would then be more of a concern in the main hall. Each gas cabinet is also ventilated to prevent gas from spreading within the facility so it would not be of any concern. It is more of a problem if a tube from the gas system is leaking within the hutch, with the exception of the inert gases. The containment of the hutch can then make the gas levels high enough to constitute severe threats if leaking. A flammable mixture can for example cause a fire if ignited by static electricity. Hydrogen H_2 is one of the flammable gases used monthly at BALDER and it has a flammable range of 4 to 75 % [19] making it likely to be within the range if the whole content of the cylinder leaks out in the hutch. Since it is so much lighter than air, it can reach those concentrations relatively fast at the ceiling. However, both gas and pressure detectors will give an alarm if they are working properly and are installed correctly, and then tell the shut-off valve to turn off the system before the concentrations become too high. The ventilation in the hutch will also reduce the gas concentrations. It is therefore very important that it works as it should.

Highly toxic gases such as carbon monoxide CO, nitrogen dioxide NO_2 and hydrogen sulfide H_2S will be used regularly and can be harmful even at very low concentrations. The toxicity may represent a higher probability risk if leaking than the flammability since it doesn't need to reach a certain concentration before being harmful. However, the flammable gases are more dangerous in case of a fire instead. This is why cabinet nr. 5 inside the hutch is of a major concern, and may be one of the biggest challenges when designing the gas system. Cabinet nr. 5 is planned to handle 5 liter 200 bar gas cylinders, and will have user supplied gases depending on the experiment. These special gases needs to be evaluated by the safety and beamline staff before they are approved. Cabinet nr. 5 is also never supposed to be used for storage of gases, only used during experiments. One of the more frequent user gases is hydrogen sulfide H_2S which is considered highly toxic. In this case, a gas leakage would mean that the whole bottle of 1000 liters (1 m^3) has a potential of leaking out in the hutch. Since this can give a concentration of 0.58 % and the risk level is 0.1 % for nearly instant death [20], making it very dangerous if a leakage occur. It should be noted that the gas is placed inside a cabinet with ventilation, the hutch has also its own ventilation making it less likely to have a gas leakage at the same time as a ventilation failure. The gas cylinder is also connected to a blow-off valve if the pressure rises. Along with the gas detector for sulfur, there are many barriers if a leak would happen. A possible hazard may be a leakage of a pipe, this could lead to severe consequences if the leakage is close to a person working in the hutch. The local concentration is then much higher and hasn't had time to be diluted. It may be unlikely for this to happen but the consequences can be very severe for persons within the hutch.

The chemistry lab may also contain numerous of dangerous gases but will not be analyzed further in detail since it is out of topic regarding this report. It is however a risk for BALDER users since they may go there to prepare their samples. Since persons from all beamlines (with proper education) are able to work in the chemistry lab, it makes the possibility that dangerous chemicals and gases are prepared there and may easier be mixed with each other if not labeled and placed correctly. By applying the proper equipment for the users in the prep. lab, they are more likely to prepare their samples there because of the distance, plus they don't need to undergo an extra safety course.

5.3 Fire

Fire is a risk at every facility and there are countless of reasons for why it might start. In the prep. lab, the most likely risk that can cause a fire is the oven. The oven is of an ordinary type and can be found in any regular kitchen. The amounts baked in the oven will most often be fairly low, a couple of grams. If so, it is probably not a high risk scenario for it to start a fire, probably less than for an ordinary oven in every household. The same reasoning goes for the exp. hutch where computer, other hardware and furniture are the potential fire threats, just as in any ordinary living room or office.

In the exp. hutch, the largest threat of fire are the gases which are analyzed in the previous section of gases and chemicals. Except for the cables and hardware, the exp. hutch also has an oven. This oven however, is very small compared to an regular oven and have an inner volume of a couple of mm^3. Even if it has a capacity of 900°, the heated volume will be so small it wouldn't affect the temperature noticeably in the hutch, even if the oven is leaking.

5.4 Electricity

Electricity at the MAX IV Laboratory has been described in section 4.10. Electricity in general is, like fire, always a risk. MAX IV and BALDER contain many different kinds of electrical equipment, and can contribute to lethal damages if not installed and maintained correctly.

In Sweden, around 3-6 persons die every year in accidents involving electricity. Most of them are either authorized electricians, laymen in their homes or children. This can be seen as an indication that as long as users aren't doing anything they shouldn't do e.g. fixing damaged hardware, then the probability of an accident involving electricity is fairly low. Extra consideration should be taken when operating the overhead crane, since it can be controlled into damaging both hardware and cables. The overhead crane requires however extra education and isn't normally operated by users. It should be pointed out to the users that if they damage something, they should be encouraged to report it to authorized personnel and never try fixing it themselves. [21]

5.5 Miscellaneous

At BALDER, there are many other risks which aren't included in the major categories. The oven in the prep. lab has beside the risk of fires, also a risk for burns if safety equipment isn't used properly and if proper safety equipment isn't provided. This may also depend on tiredness which is a factor that can increase the probability for a risks to occur. Tiredness can for example cause a user to open the wrong valves and mix the wrong gases from the control room, or to not install the right equipment at the right place during setup. It is not only a risk of safety but making the wrong decisions when tired can ruin the experiment as well. The samples can be damaged if mixing the wrong gases or just by being clumsy and dropping them etc. Tiredness is a concern for every location the user is visiting. Since the beamtime can have a long duration, tiredness will affect almost all of the users. Therefore it is necessary to try to facilitate for doing things right and not wrong, the safest way should also be the easiest to as large extent as possible.

The type of sample robot in the hutch isn't decided yet and is therefore hard to evaluate if it may form some sort of risk or not. There will be moving parts in order to irradiate different samples, but it will probably not require so much force in order to change the relatively light samples. It is also not supposed to run when persons are in the hutch. The environment in the hutch can also be quite messy. At the I811, there are tools in many locations, cables on the floor and sometimes devices that you have to duck under. This will probably not be the case at BALDER or any other beamline from the start. It can however be a problem after time, especially when new equipment is installed and users and staff disorganize tools etc. All these things can be causing injuries when for example a person is slipping on them or walks into sharp or hard edges or the overhead crane when loaded. This along with illness and other threats can cause persons to pass out, and even have greater consequences if it happens within the hutch. It can take a long time before anyone finds them there plus that the environment with gases, radiation etc. can be of a concern if the person doesn't wakes up, especially if not found during PSS. Since the room is so small and with no places to remain hidden during a PSS search, it is very unlikely they aren't found if not made intentionally.

5.6 The bowtie model

Using the bowtie model, the risks and barriers can be illustrated for a better understanding of where improvement is needed. For this bowtie model, there are two top events "Gas leakage/explosion" and "User pass out in the hutch" connected to two different hazards. The reason of why these two where chosen as top events is that they represent two of the main events at BALDER that are strongly connected to many of the risks shown in figure 13 covering many aspects. The figure shows however only a few of the many threats, consequences and barriers but gives an illustration of what can happen if the barriers fail.

Linked to the top events are the threats and consequences. The reason why a gas leakage occur is that the cylinder or that the gas system including pressure and flow meters, vents, pipes, connections etc. gets damaged. It can also be someone who forgot to close the system properly or forgot a gasket while mounting a regulator on a cylinder. Usually the pressure meters and the detectors for the different gases will alarm and close the system automatically (barriers), but they may for some reasons not be functional or too slow. As mentioned before, a leakage within the hutch can have large consequences right from the start if someone is present. A gas explosion can be triggered by an increase of the inner pressure in the cylinder itself. The main reason why the pressure increases in a gas cylinder is the increase in temperature. This could be the case if a fire starts. Since all cylinders are in 30 minutes fireproof cabinets, the fire must be very massive in order for it to heat up the cylinders to explode. At this time, the building is probably evacuated a long time ago, and there is probably not anything more to do than for the emergency service to try extinguish the fire and save what's left of the building or simply to let it burn up. An explosion can also occur for example by flammable gases that has been spread out in the air and stays within its explosion range along with some sort of ignition source.

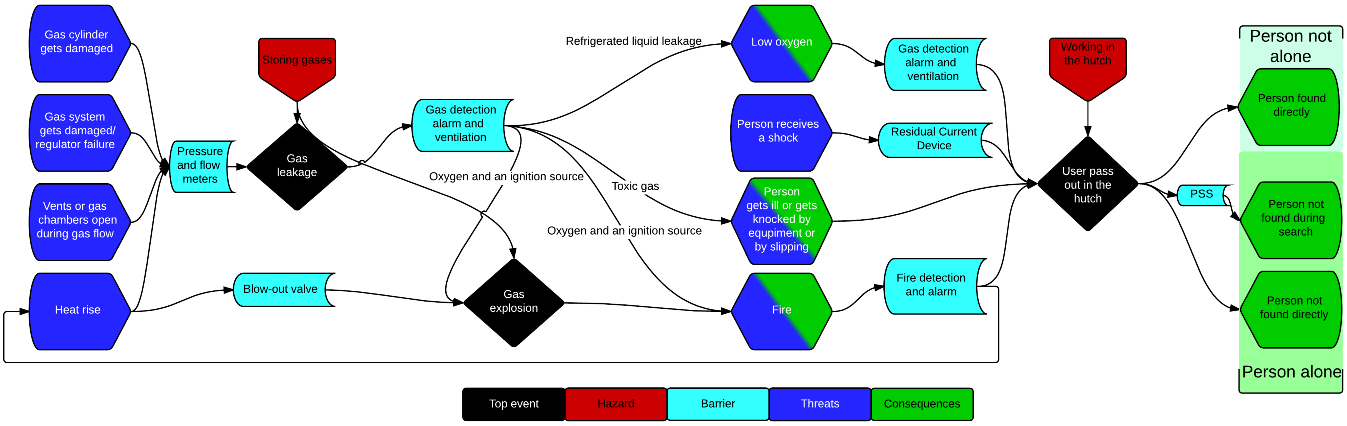

Figure 14: A Bowtie model over the three top events "Gas leakage/explosion" and "user pass out in the hutch" which are all independent of each other. Regarding the barriers, note that the model only describes what can happen if the barriers fail. The barriers will work differently depending on the threat, but in general, the barriers shut down the gas flow and close the incoming beam, and in some cases they even turn off the whole accelerator if activated. The PSS works more preventative and will deny beam access if the PSS search isn't performed correctly.

The ignition source could be static electricity being released or simply a flame. This may start a fire which then can repeat the process by making other cylinders explode, or damaging other gas pipes.

A user passing out in the hutch can happen for many reasons. Some of these threats can be possible consequences of the other two top events for many reasons, but it isn't necessary and they are not dependent of each other. For example a fire can start because of a gas explosion, but it can also start from electricity or an oven. Low oxygen levels is a threat probably caused by a leak from the liquid nitrogen gas tank. It may also be from a failure of the ventilation, but it isn't likely since the door is (at least should be) open when persons are present in the hutch. Some threats are likely to happen at other places than BALDER and MAX IV as well like fire, shocks from electricity, diseases and getting knocked out by for example slipping. The consequences depends on what type of threat causing the accident and how it happened, but also for how long it takes before the person is found. It can be a risky environment, especially if a person works alone. The risks also varies depending on many different factors as which types of gases that are used.

There are more barriers than described in this model. For example can the safety course be seen as a barrier in order for a user to take the right safety measures during beamtime. The gas cabinets insulates the gas cylinders from the environment. To reduce radiation, the hutch is made by a thick layer of lead etc. This bowtie model is designed to illustrate some of the main parts for three of the most interesting top events and probably highest risks specific for the beamline BALDER, where gas and radiation are the most noticeable risks.

6 Result

The identified risks of importance are evaluated and put into the risk matrix for probability and consequences below in figure 15. Note that accidents from these risks may also mean severe damage to the equipment, this is not taken into consideration due to the user perspective of this report.

The risks in the figure can be categorized depending on how general or specific they are for BALDER. The general risks exists on most regular working places, for example fire and electricity. The ones that are special for MAX IV and don't exists on most regular places are especially the radiation and in some extent the gas handling and lasers (not at BALDER). The more specific risks for BALDER compared to the other beamlines is the gas handling; high gas pressure, high gas temperatures and the containment of gases inside the hutch. Some of the more general risks are however higher in this environment since other specific risks can contribute to both their probability and their consequence. For example can a gas leakage lead to a fire as seen in figure 14. The reason of a categorization like this is to separate the work and to make it clear who has which responsibility. For this report, a categorization might be good in order to separate the risks that needs to be dealt with for BALDER specifically. This report may also work as a substrate for other beamlines to see what type of risks that are specific for them. The general MAX IV risks are something to work further on as well, especially for the safety staff.

As can be seen in figure 15, the evaluated highest risks are to get electrified, full scale fires and gas leakages in the hutch containing toxic or other type of harmful gases. Since these risks can trigger each other, it may be a good idea to isolate them further from each other, for example by thermal insulation gas pipes and certain boxes for electric hardware. There should also be very strict rules of how to manage toxic gases within the hutch. Since all gas flows are automated, to mount the gas bottle should probably be the last thing carried out before starting the PSS search. It should maybe require a pressure safety test with a harmless gas before. The gas bottle should always stand inside the cabinet nr. 5 when inside the hutch because of its ventilation. All users monitoring toxic gases should perhaps undergo special safety instructions by the beamline or safety staff. Radiation, considered by many the most characteristic risk of MAX IV, is in this matrix evaluated lower than most other risks. One reason is that radiation is a relatively easy risk to reduce with thick lead walls and concrete. It is also dealt with at high extent at every hard X-ray beamline including the linac and the storage rings. The radiation is also far higher in the linac and in the storage rings as well as in the optics hutch compared to the exp. hutch which this risk describes. There is also the PSS, and even if someone is left in the exp. hutch while the beam is running, the concern will probably

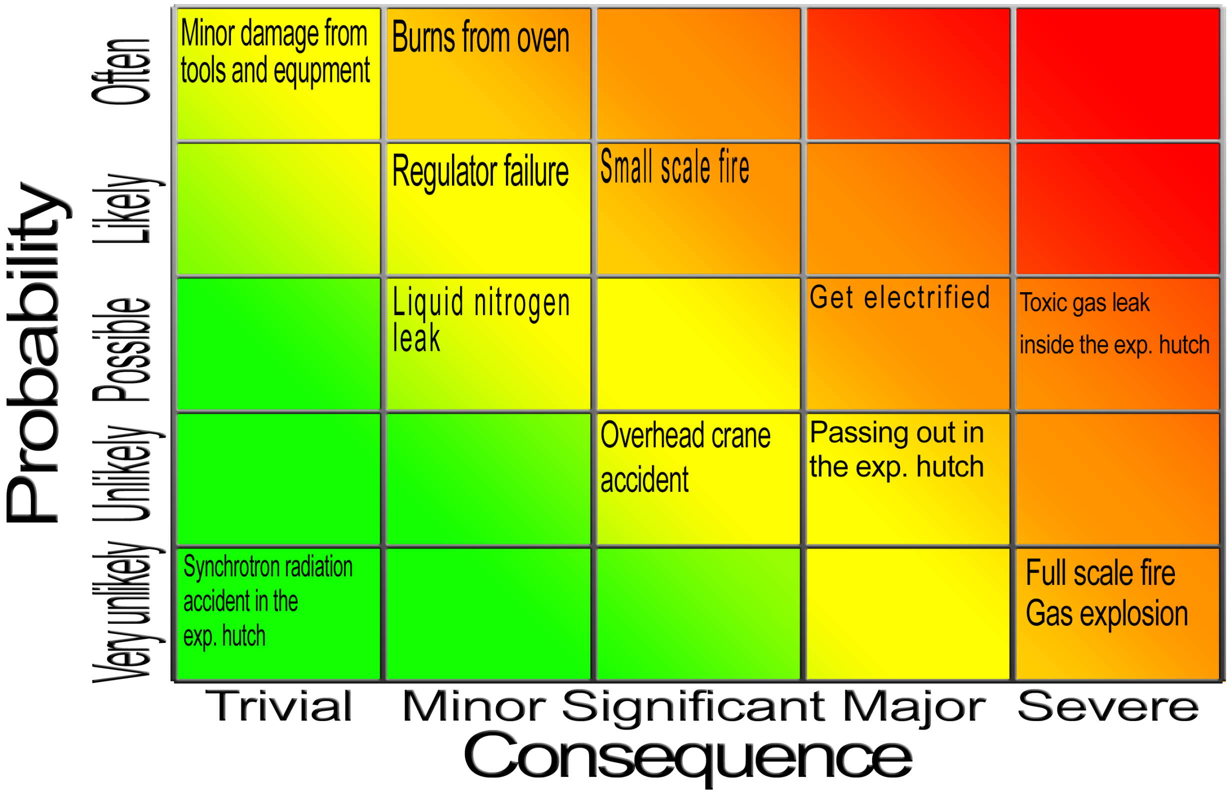

Figure 15: The matrix shows some of the most noticeable risks for users at BALDER evaluated in a risk matrix. The table below describes the meaning of the different probabilities and consequences.

Probability	Event occurring interval (years)	Consequence	Description
Very unlikely	>50	Trivial	No treatment required
Unlikely	31 - 50	Minor	Minor injury requiring First Aid treatment
Possible	16 - 30	Significant	Injury requiring medical treatment
Likely	6 - 15	Major	Serious injury requiring special medical treatment
Often	≤ 5	Severe	Loss of life or permanent disability

more be of how it could happen rather than the actual damage.

The risks are placed in the matrix by evaluation of different aspects. The probabilities is in a large extent based on previous accidents and incidents at MAX-lab and the I811 since they are so similar laboratories. The consequences are quite hard to determine since it vastly depends on what really is meant by the different risks and accidents. Here below is every risk from the matrix in figure 15 described how it is evaluated.

- Radiation accident in the exp. hutch: Very unlikely and has never happened in the the history of MAX-lab, only in the nuclear research facility in the basement. In the exp. hutch, the radiation exposure will probably be less than for a visit at the dentist depending on the duration.
- Minor damage from tools and equipment: Small cuts or crushing injuries, slipping on the floor. Happens every year and does most often not need any certain treatment.
- Burns from oven: The prep. lab oven, will probably occur as likely as at any other conventional oven. The usage ratio of the oven will however probably be quite low. The burns may need to be cooled down.
- Regulator failure: Makes the pressure increase at the secondary side. It's considered likely to happen within 15 years because of the high gas usage at the beamline. It will probably not result in anything more than a release of the pressure vessel and an alarm. It can however lead to a gas leak both inside and outside the hutch.
- Liquid nitrogen leak: A possible event, will probably not be more than a small frostbite. At worst in a very unlikely event, it could lead to lack of oxygen and a user passing out in the hutch.
- Small scale fire: Is considered likely and at MAX-lab, small cable fires happen every year. May not require any treatment at all, it may however need to be examined by a doctor due to inhalation of smoke.
- Overhead crane accident: An unlikely event, especially since most users won't operate the crane. The consequence can be anything from a push from the moving object or getting heavy equipment dropped over a person.
- Get electrified: A possible event, especially if someone try to fix broken things by themselves. The consequence depends on the type, duration and magnitude of the current and how it passes through the body meaning everything from a trivial to a severe consequence. This event refers to the more rare type of electrical accidents with a high current traveling through the body.
- Passing out in the exp. hutch: Unlikely and has never happened at MAX-lab. May be almost trivial in some cases to severe in others. It is considered major since the person is often alone in the hutch and it may take time before he or she is found. In cases of for example heart and brain diseases or bleeding, the time is crucial and treatment is needed as fast as possible.
- Full scale fire: A very unlikely event that can be catastrophic. The users are hopefully alerted by the fire alarms in time to evacuate.
- Gas explosion: A very unlikely event with a possible severe outcome. It is perhaps even more dangerous than a full scale fire because of the fast sequence of events.

- Toxic gas leak inside the exp. hutch: Not so likely to occur since toxic gases are contained in a cabinet. Although, still possible through pipes or gas chamber leakages. The consequence may be severe depending on the gas and concentration along with the exposure duration.

7 Discussion

It should be easier making the right decision than making the wrong one. If applied to risk analysis, the right decision should always be the safer one. At the MAX IV Laboratory, it is easy to see how improvements have and is made at the new facility. The older MAX-lab has been constructed and developed over a long time. Safety at this site has been updated and improved continuously, still not regulated and not always reaching up to safety standards as newer similar facilities has. This is probably because it would require major revisions of both the construction and regulations which may not be viable in an economical and time perspective, especially due to its closure and the focus of MAX IV instead. However, it doesn't mean that the safety at MAX-lab is bad, especially not with its preconditions. But compared to the new MAX IV, where the safety aspect has been at the agenda since day one of the construction, a lot of things have been improved regarding the safety according to my opinion. The improvements also regards BALDER specifically compared to I811; the PSS, chicanes, the floor plan including prep lab, placing of gas containers and the automation of the gas system. Also, just by placing a type of sample robot inside the hutch will (according to plan) drastically reduce the exp. hutch visit frequency for the users. However, there is always room for improvement and keeping the safety as high as possible is a continuous work. According to the PDCA cycle one might say that this report mostly represents the C - Check and a little of the P - Plan in the first cycle. The check may include everything except the gas system which more or less have been developed but not constructed under the time of writing. Most safety measures have been planned long before this report was started and has been constructed to some extent. This report, is more a view from the outside of someone who hasn't been affected or influenced for so long by the general opinions.

My result, as illustrated in figure 15, is not exactly what I expected at the start, comparing the radiation risks against the risks of gases. As I have mentioned before, the safety measures against radiation is relatively easy to carry out in form of thick walls. And parts not so easy to make like the PSS is well thought trough instead, at least at MAX IV. It is clearly a risk that everyone at the MAX IV Laboratory is well aware of and is talking about almost daily. A problem with this may be that other risks become secondary. My impressions in the beginning of the research was that radiation was the considered highest risk at MAX IV. It is probably the case in the linac and the storage rings and probably the optics hutches as well, but not necessary at the rest of the beamlines. This is however one of the reasons I was assigned to look closer at BALDER, since it will be able to handle gas mixtures at high pressure. This is in my opinion a very advanced system to construct and probably more advanced compared to the radiation safety. It should perhaps be the first thing to investigate when building BALDER and other beamlines dealing with harmful gases. On the other hand, it may be difficult to construct the gas system without knowing the properties and dimensions of the hutch. Perhaps it could have been discussed more in advance with the persons constructing it making it not so stressful to finish within the time limit. Also, as long as research progress, the need for more and more harmful and rare gases will increase which may probably lead to more frequent usage of dangerous gases at BALDER. Together with the gas system, the ventilation should be checked regularly in order to prevent gas accumulations. Other than that, the rest of the results can be considered fairly similar to what one might expect with similar risks compare to industries.

Another thing to consider may be the education of the users. The new safety course is under development and there are some things that might be mentioned that isn't conventional in a safety course. First of all it is a good idea to mention something about tiredness while working at the beamlines and how it affects the mind. It can encourage people to plan their work time ahead in order to prevent them from making difficult decisions while tired. As mentioned, it should be easy making the right decisions but when tired, the right decision doesn't always seem right. The safety course should also encourage users not to fix broken equipment by themselves, especially if it involves electricity, they could get injured. People can and are making mistakes and to have a forgetting environment and culture, it will hopefully lead to more damaged equipment reported and repaired to thereby increasing safety. The practical beamline education by the beamline staff should perhaps be mandatory for every user operating at the specific beamline as well. Today only one needs to participate in this part of the safety course and is then to tell the rest of the users. In my opinion, it can lead to misunderstandings and wrong decisions made, especially if the educated person isn't present at the beamline. The practical beamline education works partly as a barrier to prevent accidents but can in this case easily be set aside. However, it can contribute to a greater work load for the beamline staff, but shouldn't in most cases be increased significantly since all of the users can be educated at once.

BALDER is at today's date not finished and will not, according to schedule, be totally complete before the end of 2016. Some other things to consider in order to increase safety before it is finished is the placement of the PSS search buttons. To improve the search further, or for future beamlines, it could be a good idea to place some buttons at the experiment table instead. This would ease for the searcher to not have to thinking of turning around from the wall but are forced to do so automatically. My own experience of performing a search is that you look more into the wall than around. The new PSS at MAX IV will however have a minimum time between pressing buttons which may reduce this relatively minor problem. Another perhaps bigger issue which isn't decided yet is how the transportation of flammable gases will be carried out while BALDER is operational. It is said today that flammable gases will only be placed at the beamline during beamtime. This will require transportation of for example H_2 back and forth to the gas containment room many times a month which also can be considered as a risk. The cylinder could be dropped into the ground and get damaged, or the truck carrying it could drive into something or someone. If the MAX IV staff or users themselves will be responsible for the transportation isn't decided either. At the same time, it is probably not a good idea to have harmful gases placed around the site while unused.

8 Risk reduction suggestions

In order to conclude how risks from a user perspective at BALDER can be reduced, here are some suggestion of improvements:

- Investigate the gas handling of the gas cabinet inside the hutch (cabinet nr. 5) further to prevent toxic leakages.
- Consider a passage between the prep. lab, control room and the hutch preventing unnecessary contamination by samples. This could also be applied to future beamlines.
- Improve the safety instruction routines for arriving users.
- PSS buttons may be placed on the exp. table for a better view.
- Develop the gas transportation routines between BALDER and the gas storage room.
- Mirrors around the beamline to prevent collisions.
- Apply systematic incident reporting.
- Facilitate for incident and damage reporting from users and urge them to do so in the online safety course.

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