Safety aspects for the design and operation of new accelerator facilities

1 Introduction

The planning of new accelerator facilities has to consider the aspects of safe operation and protection and rescue measures in case of accidents.

First of all, the facility has to be regarded as a source of ionizing and non-ionizing radiation depending on various beam-material interactions:

a) During the acceleration cycle in the synchrotron, a small fraction of the partially stripped ions will loose electrons due to interaction with the rest gas. These ions leave the orbit and hit the beam tubes, thus inducing radiation. The vacuum specifications for SIS100/200 are such that these beam losses are tolerable. The radiation has also to be kept to a low level in order to avoid the quenching of the superconducting magnets. Nevertheless, the required shielding is quite substantial what made the choice of an underground installation for the SIS100/200, also motivated by ecological considerations, rather obvious.

b) With the help of collimators and scrapers the extracted beams are sometimes shaped into special geometries . These are strong sources of radiation, which need to be shielded locally by thick iron and concrete walls.

c) The target inside is another source of radiation, since it is the very spot where the interaction of the beam with the target material sample is to take place. Often the detectors do not capture all particles produced and a full shielding of the experimental cave is indispensable.

d) Finally, the beam, which has not undergone any interaction, is dumped into the ‘beam dump’ where all the energy is lost in nuclear reactions and electromagnetic stopping.

e) In addition, worst case scenarios of, e.g., lost beams due to the malfunction of beam optics elements, have been studied and taken into consideration in the elaborate shielding project. We have opted for shielding materials sufficiently thick to absorb also all of the produced muons.

A survey was made regarding the generation of radioactivity in the accelerator and the production of radionuclides in the cooling loops and in the air of the accelerator tunnel. Doses have been estimated for these areas. The impact of high-energy neutron radiation, which escapes into the environment, is described by an estimate of the production and the migration of long-lived radioactivity into the ground, and on the associated exposure of man through consumption of drinking water enriched by these radionuclides.

In addition, a notable level of ionizing radiation may even remain during shut-down periods of the accelerator as a result of activation of target and shielding material. Estimates are given of its impact on the human body during rapid access after stopping the machine in its running period as well as during the dismantling phase at the end of the accelerator facility's lifetime.

Secondly, the safety measures are conditioned by the underground location of the accelerator, experimental areas, as well as other auxiliary buildings and installations.

Thirdly, the operation of the accelerator facility will include additional risks, e.g., from a possible exposure to (non-ionizing) high-level electromagnetic fields, from the handling of chemically hazardous substances, from the operation of high-pressure vessels and pipe-lines, and so forth. The main risks and the related recommended safety measures will be discussed in the following sections.

In addition to the risks originating from ionizing and non-ionizing radiation an analysis was performed regarding the impact of the facility on the environment, the danger of fire and of toxic substances, as well as other potential sources of danger. Recommendations for protection and safety measures are made which will influence the final design of the facility.

2 Ionizing radiation

Ionizing radiation is produced during the operation of a heavy ion accelerator, especially at sites of sometimes substantial beam loss, as described above. In order to protect persons and the environment from exposure, ionizing radiation can be attenuated by shielding installations surrounding the radiation source. In areas of access to either technical, scientific or administrative personnel (GSI premises) or to the general public (the woods around GSI), dose limits given by the Radiation Protection Ordinance must not be exceeded. Assuming a worst case scenario the additional annual dose for the population, arising from the operation of all facilities at the GSI site, must be less than 1 mSv, including the dose caused by ingestion, inhalation, submersion, and direct radiation from the accelerator. Ingestion, inhalation, and submersion may contribute less than 0.3 mSv/a. According to the limits of the German Radiation Protection Ordinance the dose must be less than 3 μSv/h in uncontrolled areas and less than 0,5 μSv/h outside the facility.

An overview of the locations where a high level of neutron production and activation can be expected is given in *Figure 2.1*. These are the areas of the Super-FRS, of the anti-proton target, and the injection and extraction building. There, the beam or the targets must be shielded with concrete walls of about 10 m thickness to reduce the dose outside the shielding to values of 1.0 mSv/a or less than 3 μSv/h respectively.

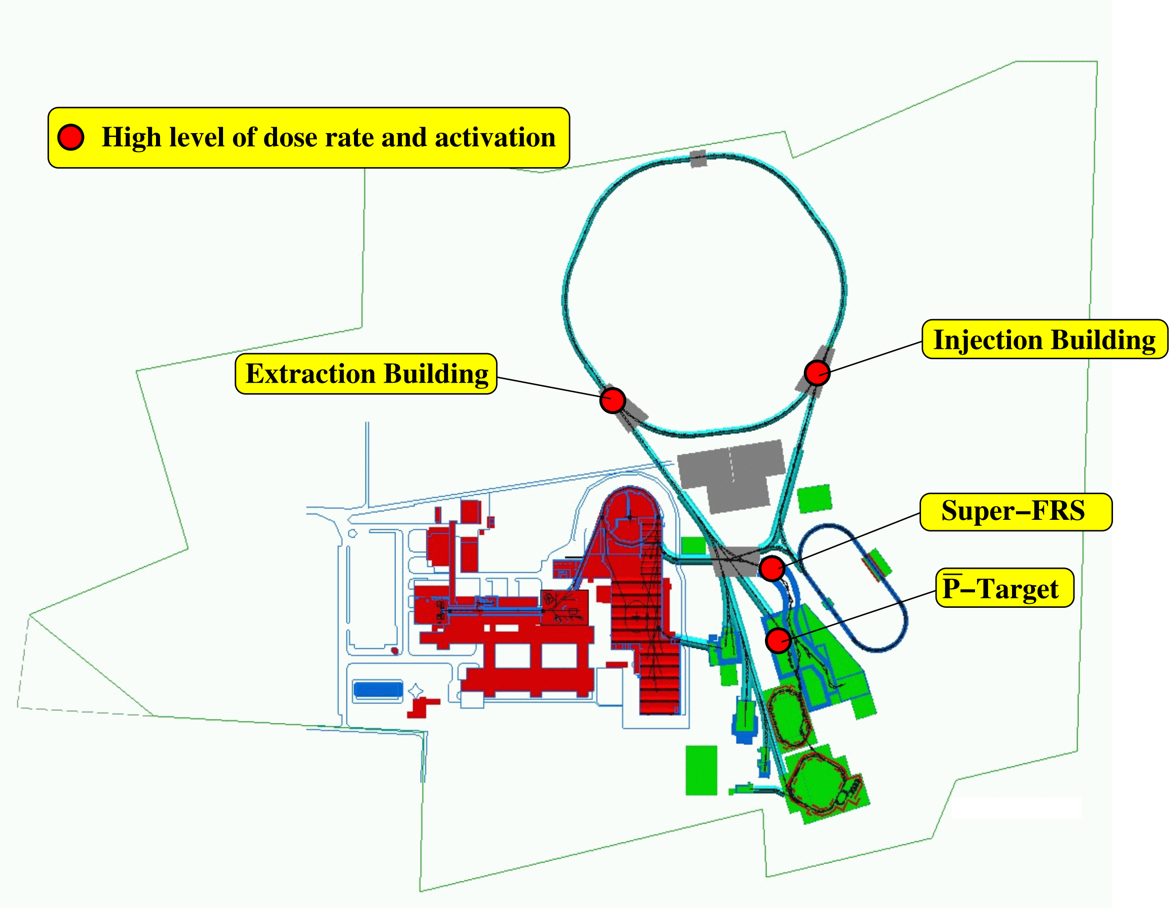

Figure 2.1: Overview of the facility with locations of high doses: injection and extraction buildings, the Super-FRS (Superconducting projectile FRagment Separator) and the anti-proton target.

The main aspects of radiation protection will be discussed in the following paragraphs. For dose estimates in this context, the production of neutrons by high-energy heavy ions will be assumed to depend only on the number of accelerated ions per second × specific energy of the accelerated ion × the number of nucleons of the accelerated ion. Thus, an uranium 238 beam of 10^{12} ions per second and 1-2 GeV/u specific energy will be estimated to produce the same neutron flux as a proton beam of 10^{13} particles per second and 30 GeV. However, since the range of protons is larger this estimate will be an upper limit for the heavy ions.

2.1 Doses in access areas

The accelerator vault at 24 meter beyond ground level will be surrounded by 1.5 m of concrete and covered by about 18 m of soil. The dose rate resulting from a total beam loss will be hardly detectable, being orders of magnitude below the natural radiation level.

The access pits require special attention. Access areas near the location of a potential beam loss have to be shielded by additional concrete or by a sandwiched mixture of concrete and iron. Since iron has the smaller radiation length it would be used as the inner layer of such a shield. For a loss of 10 % of an uranium beam of highest specific energy and highest intensity, i.e. a loss of about 1×10^{11} uranium ions of 2 GeV/u, the lateral shielding has to correspond to about 1800 gcm^{-2}, i.e. for a distance of 8.5 m, with shielding provided by a 6-m-thick sandwich of iron (~ 1.8 m) and concrete (~ 4.2 m), or for a distance of about 10 m with a shielding of about 7.5 m of concrete, in order to achieve 3 μSv/h. Such a 'worst case scenario' is not at all realistic since the beam loss resulting of such an accident would severely damage the accelerator structures and the beam lines.

Since we are dominantly operating so called fixed-target facilities with their specific kinematics, experimental control rooms and other places where there might be people, should neither be placed behind the target nor in dump or collimator areas.

Beam stoppers or beam dumps have to be constructed in a special way, to assure the full containment of the beam.

The activation of accelerator parts of SIS 100/200 can be scaled from the experiences at SIS 18. If the order of magnitude of the beam losses at SIS 100/200 is comparable with those observed at SIS 18, doses of up to 2 Sv/h must be expected at certain locations along the beam lines, and dose rates of about 10 mSv/h at a distance of 1.5 m from the beam lines. The activation, and thus the resulting dose, will decrease with an initial half life of days, and subsequently with a half life of weeks. Therefore, it is advisable to carry out repair or maintainance work after allowing one or two weeks of decay time. However, it is necessary to control the access to these areas and to use robots for such repair or maintenance operations. In order to minimize the radiation burden for the service personnel, it is necessary to have spare parts on hand for elements important for the operation of the accelerators, and to have a building or area for a safe storage of the activated parts .

It is also necessary to keep movable leaden shielding equipment and lead glass.

The beam losses at SIS 18 are expected to be lower in the future, since the progress of beam detecting and handling techniques and the advanced programming software may lead to a better beam control and thus to smaller activation rates as well as to smaller dose rates near parts of the accelerators and beam lines. In addition, the accelerator will be equipped with superconducting magnets the radiation tolerance of which will determine the limit for tolerable beam losses. So, the above scaling for the expected dose rate may only apply to the worst case.

2.2 Activation

For estimating the activation of accelerator parts, as well as the cave walls, floors and air, etc., the following assumptions have been made:

The full uranium beam will be stopped in a thick iron target in the accelerator vault for one week, (as may be the case for long accelerator studies). During this time, the air in the vault is not exchanged. After one week all of it is blown out into the environment through a chimney without any specific filters. The height of the chimney stack should be 37 m above ground level (comparable with the chimney stacks at the UNILAC and the SIS18). Since this is below the legal limit, measures will be taken to stop the beam in the tunnel in a properly shielded and sealed beam stopper. This will avoid air activation and pollution of the surrounding environment.

The above mentioned assumptions are not realistic but represent a worst case scenario but even then, the highest dose for persons will be less than 250 μSv in one year.

For estimating the activities in the experimental areas, the following assumptions were made:

An uranium beam of 1 x 10^9 ions/s and 2 GeV/u is stopped in a heavy metal target. The air stays the same in the experimental cave. The irradiation experiment will last one month and will be repeated once a year. One tenth of the allocated beam time is used for changes in the experimental set-up. The experimental cave is entered immediately after the beam shut-down. The resulting dose rate is caused by beta and gamma submersion and may reach 1 to 2 mSv per year. In the above passage, only the activation of air by secondary particles has been considered.

The direct activation of air – if the beam is travelling through air (not in a beam pipe) - has to be examined, when details are given by the experimental physicist. If the beam travels through air for a distance of some meters the resulting activities of the air will be an order of magnitude lower than the values given for the activation by secondary particles. Special areas of high activation like the synchrotron ring cave below the surface or the RIB or Antiproton production target stations could hermetically be sealed off and the air exchanged through special filters, if required.

Noxious Compounds:

Toxic gases, e.g. ozone (O_3) and nitrogen oxide (NO_2) can be formed by the ionization of air by electrons and photons around accelerators. This process is thoroughly discussed in several reports, especially in (1), (2) and (3).

Radiation, important for the formation of ozone and nitrogen oxide, is produced to a lesser extent by a heavy ion or proton accelerator than by an electron accelerator. The concentrations of ozone and nitrogen oxide in the air have been measured since 1986 near the air outlets of LEP of CERN. The results of these measurements have been compared with other measurements near Geneva in districts similar to the surroundings of CERN. The measurements of ozone and nitric oxide near CERN did not reveal any influence of CERN. Almost all measured concentrations were lower than those at the nearby village of Anières. These results can be adopted for SIS 100/200. However, it is recommended to install measuring devices where the highest concentrations of ozone and nitric oxide may be expected, due to the height of the air outlet pipes and meteorological conditions.

It has to be mentioned that the concentration of ozone and nitric oxide inside the vault of the accelerator should be monitored if the accelerator is to be entered after an interruption of the acceleration process. The hazard of the radioactive gases is higher than that of the noxious compounds.

Water activation:

Water flows through the cooling pipes of the accelerator, is activated to a certain degree and will finally reach a heat exchanger in a remote location. In addition, ground water may flow outside of the tunnel walls carrying its radionuclides away from the facility site. For both we require thorough risk analyses.

Reliable values cannot be given before the cooling water loops have been designed. However, for a first estimate, the data based on the SIS 18 operation have been used and scaled up to higher energies and intensities:

We assume that the cooling water will be utilized for one month and that only the generated ^{3}H and ^{7}Be have to be examined for being potentially dangerous long lived products. The result of the estimates is encouraging: the content of ^{3}H will be below the limits given in the Radiation Protection Ordinance. ^{7}Be will be caught in the ion exchangers of the cooling loops and will therefore not get into the waste water. The half lives of the produced nuclides of ^{11}C, ^{13}N and ^{15}O is so short that after the decay time of only one day the activity is rather low and therefore far beyond detectability levels.

The dose rates near the pipe of the cooling water loops have to be monitored during the operation of the accelerator. The doses measured at the surface of the cooling loop pipes of SIS 18 were extrapolated to the expected SIS 100/200 conditions but only doses below 0,5 mSv/h are expected. However, these pipes should not traverse rooms accessible to GSI staff and their surroundings should be kept free, in case additional shielding is required.

These precautionary measures may be superfluous because SIS 100/200 will be an accelerator with superconducting magnets where the cooling water will not come as close to the beamline parts as in SIS 18.

The estimates of the activation of the soil around the accelerator, established for SIS 18, have been scaled up for SIS 100/200. However, while the SIS 18 is located at ground level with the water level just a few centimeters below, the SIS100/200 will be located in a depth of 24 meters where rock and soil are rather free of flowing water (see chapter on Civil Construction). The Radiation Protection Ordinance contains limits for the emission of radioactive substances into the ground water. If we assume that all of the activity produced in the soil is washed out into the ground water, the limits mentioned above are exceeded by a factor of 1000 and more. Thus, the produced activity calls for a closer examination. The activity will be generated in the grains of the soil and will then diffuse to the boundaries of the grain. But since it is the diffusion of a solid into solid material, it is a very slow process which will finally end up in an equilibrium after a certain but unknown time. After that no dilution will occur.

In a worst case scenario (and contrary to the data from depth drillings, assuming groundwater at the depth of the accelerator) there will be an equilibrium between ions in liquid and ions in solid phases. For averaged normal concentrations, the relation between the respective specific concentrations will be 1 : 100 for sodium and 1 : 1000 for calcium (water : soil). A similar relationship will be valid for other nuclides. The relation 1 : 100 (water : ground) can be taken as a lower limit. However, the soil has to be analyzed for concentrations of different elements, in order to verify these assumptions. In this worst case scenario, the activity washed out with the ground water is calculated to be lower than the limits stipulated in the Radiation Protection Ordinance, except for ^{22}Na.

The speed of nuclide migration in the soil lies between 10^{-4} to 10^{-7} m x s^{-1}. At the GSI site, the ground water flows in a westward or south-westward direction, with velocities of about 5 x 10^{-6} to 5 x 10^{-9} m x s^{-1}, i.e. 13 to 0,013 m/month. The next bore holes for water, going down for 20 m and more, are to be found at a distance of about 2 km from GSI at the outskirts of the village of Wixhausen. Thus, the ground water needs about 10 years to reach these places. During this time the activity of ^{22}Na will have decayed to 7 % of the initial value and it is diluted by dispersion into the neighbouring ground water. At places of possible water extraction the ground water will only contain activities far below the limits of the Radiation Protection Ordinance.

On the basis of the data of test drillings, we can conclude that the underground solution of the accelerator with its foreseen shielding does not pose any health risks from radiation.

2.3 Storage and Handling of Activated Parts

As pointed out above, the remnant activity in all places of beam loss, i.e. in the accelerator parts, in the environment close to the machine, at the target stations or in the beam dump needs special attention. The longest-lived isotope produced in an iron block is ^{60}Co with a half life of 5.3 years. With a beam power of 100 kW for SIS 100/200 during 10 months of operation for about 25 years, a total radioactivity of approx. 440 TBq will be produced. After a final shut-down, this activity will diminish to 220 TBq after five years [5]. In the activated superconducting coils of the dipoles one will find nuclides of the rare earth elements which have half-lives of 10 – 15 years. In the case of a total dismantling of the accelerator, these parts need to be stored in a shielded area for about 50 years.

Activity with elements of various lifetimes will also build up in the shielding material, either in the iron (see above) or in the concrete [4]. In activated concrete, the major component of the long-lived isotopes is ^{152}Eu with a half-life of 13.3 years. However, Europium is only a trace element in the concrete and its quantity therefore very limited. In summary, the vault of the accelerator has to be monitored for a period of about 10 years and access to it must be restricted.

If the accelerator and the experiments have to be decommissioned after the final shutdown, the vault of the accelerator should be used as a repository for the activated parts. However, there should also be a repository for activated compounds during the operation time of the accelerator.

2.4 Accessibility of the accelerators and experiments

During operation, there is access neither to the accelerator nor to the experiments . If the beam is interrupted for short maintenance work or for changes in the control instrumentation it has to be guaranteed that

1. no beam can reach the areas accessible to personnel
2. a period of time for proper cool-down of the induced radioactivity is imposed automatically
3. the persons entering such areas are identified and wearing personal dosemeters
4. these persons are instructed about the dangers of their tasks and are able to carry out their duties
5. all persons have left the accessible area before the the accelerator is restarted.

Personal dosimetry has to be in accordance with the licensing and surveying authorities.

2.5 Survey of the radiation level

The new Radiation Protection Ordinance specifies effective doses for the personnel of the plant and for the public, as was also mandatory with the former ordinances. In order to fulfil these requirements and in order to be always informed about the radiological situation, a net of continually registering survey stations will be mounted, equipped either with integrating dosemeters as TLD’s (thermoluminescence dosemeters) in moderators or with glass dosemeters.

3 Industrial Safety

The operation of electric and magnetic devices such as high-frequency sources, magnets, power supplies etc. produces electromagnetic stray fields of various strength. Substantial electromagnetic impact may appear inside the accelerator building and the experiment locations. Electromagnetic fields are known to produce health effects, especially in the sense organs, in nerve and muscle cells, and in the heart. The biological action may partly be explained by the production of heat but there is yet no full understanding of the underlying mechanisms. The upper limits of the officially tolerated electrical current, the current density, and the specific absorption rate depend on frequency (see the following table).

Table 3.1: Upper exposure limits for areas of exposition level 1 (working areas, revisable operating areas)

Frequency	Effective electrical current J[A/m2]	Whole body mean value SAR [W/kg]
0 – 1 kHz	0.010	3)
1 – 30 kHz	0.01 f1)	3)
0.03 – 10 MHz	10 f2)	0.4
0.01 – 300 GHz	3)	0.4
1) f in kHz 2) f in MHz 3) Not relevant		

For the estimation of the electromagnetic exposure, DIN VDE 0848 “Sicherheit in elektromagnetischen Feldern, Teile 1, 2 und 3” will be applied. Precautionary measures can be the following:

Application of high-frequency shielded devices which prevent inadmissible exposures.

Areas of enhanced field strength should be simulated by calculations and later be checked by measurements.

Installations which obstruct the entrance to or the trespassing through areas of high electromagnetic risk.

In the absence of accepted technical guidelines such as the DIN VDE regulations, the construction of devices or facilities can only be carried out under certain conditions. Deviations from existing regulations may be legitimate when achieving the same level of security, using other preventative measures, as required by the official regulations.

The Supervisory Safety Boards have to check and to decide whether the proposed measures meet the official regulations in this case.

The contact of air with cryogenic devices may result in a selective condensation of oxygen. As a result, the concentration of oxygen can rise in certain areas and cause a substantial risk of inflammability or even explosion. Therefore, appropriate isolation (monitored vacuum isolation combined with adequate conventional insulation) has to be implemented.

If, for some reason, a magnet looses its superconductivity (a so-called quench) there will be an increase in temperature which may lead to a sudden evaporation of helium in the cooling system. In such a case, the excess pressure has to be released by means of a vent (for example Kautzky valves). The evaporated cooling gas may be collected in a pipeline system and recycled afterwards.

Standard as well as special procedures for fire prevention in enclosed or underground areas should be foreseen in all parts of the accelerator installations, in the experimental set-ups, in the cabling, and in the buildings, with special attention to the less accessible areas. These include the fire sectors, the installation of fire alarm devices, the usage of non-inflammable building materials , and the installation of extinguishers. Where radioactive materials are stored, special fire protection guidelines have to be obeyed, depending on the activity and the isotope under consideration. Aluminium should not be used as a constituent of beam lines and experimental set-ups since it would speed up a fire rather than containing it.

In case of a fire hazard, people must have the possibility to escape from the underground accelerator tunnel from any point of intervention. Consequently, manholes have to be installed at adequate distances in the tunnel. Applying common industrial safety regulations, the following maximum distances are permissible :

- 35 m from the working place to the room exit
- 50 m from the working place to a safe area

In coordination with the responsible authorities, one has to define adequate distances for the manholes.

Where robots (or electromechanical devices in general) are used for certain operations the range of action has to be partitioned off by barriers or other means. Robots must not obstruct passageways but must allow unhampered evacuation in case of danger.

Gases under high pressure have to be stored outside the accelerator building, especially, if they are inflammable. Suitable storage cabins should be provided.

Ionizing radiation leads to the production of radicals in the air which can chemically be transformed into toxic compounds, such as ozone or nitrogen oxides. This has to be taken into account for access control and air conditioning (see also chapter 2.2)

As was demonstrated by a deliberate release of superfluid helium at DESY, there should be no risk of asphyxiation caused by the release of liquid or very cold helium. The observations at DESY showed that a cold helium cloud can easily be detected by the naked eye and that there will be enough time to leave the affected area before the concentration of oxygen gets too low. Possible preventative measures have to be discussed with the supervisory board.

The use of nitrogen in the tunnel is forbidden, since in case of leaks this gas will lead to asphyxiation.

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This section, as all the other sections of this document, was prepared with the help of many individuals. The appendix lists the names of all the individuals involved in the CDR document, from the contributions to the science discussions, workshops and working groups to the research and development, the detailed scientific and technical planning activities, and, last not least, the drafting of this Conceptual Design Report.

The following people contributed to this section: Johannes G. Festag and Georg Fehrenbacher.

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