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Radiation Protection Issues for a Beam Power upgrade of the ISOLDE facility

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Abstract

In the plans for a High Energy and Intensity (HIE) ISOLDE facility, it is proposed to increase the average proton current on the ISOLDE isotope production target by up to a factor of five compared to today, to 10 µA or 6.25 10^{13} protons/s. This increase will have numerous consequences for radiation protection in a facility that has been constructed for a maximum proton current of 2 µA. In this report, the impact of such a beam current increase on shielding, activation, radioactive contamination control, releases into the environment and waste handling and storage is briefly described.

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1 *Introduction*

In the ISOLDE facility, radioactive isotopes are produced by proton bombardment of a thick target. The products are ionised, accelerated to an energy E = 60 keV, mass-separated and transported to experimental stations.

At present, the production target is bombarded by a protons with E = 1.4 GeV. The beam is extracted from the PS Booster PSB in pulses, each containing up to $3\ 10^{13}$ protons. The PSB can deliver one pulse every 1.2 seconds, half of which are dedicated for filling the Proton Synchrotron PS. The average proton beam current on the target is therefore 2.0 μA at the energy of 1.4 GeV, resulting in an average power dissipation of 2.8 kW in the target and on the following beam dump.

A recent proposal from the ISOLDE Group envisages to increase the average particle current to 10 μA, partly by making use of a faster cycling rate of the PSB, but mostly by the availability of higher currents of low-energy protons than today from a potential new linear accelerator, LINAC 4. This note highlights the different radiation protection issues resulting from the increased particle current in the projected facility, which is called High Intensity and Energy (HIE) ISOLDE.

In the chapter 2, the shielding of the target area with respect to the experimental area and to the zones accessible to the public around the facility against stray radiation from the target is described. Chapter 3 assesses the activation of the targets and the target area and the resulting radiation dose to personnel. Chapter 4 addresses protection against radioactive contamination. Chapter 5 treats gaseous and aequous releases from ISOLDE into the environment and chapter 6 reviews the situation with respect to radioactive waste from ISOLDE.

The aim of this report is to point to the areas where the present provisions for radiation protection are insufficient for operation of HIE ISOLDE and where investment in technical solutions and manpower are required. The report is partly based on a Technical Note from the year 2000 [3], which came to similar conclusions.

2 *Shielding of the target area*

The purpose of the shielding around the target area is to protect members of the public outside of the facility and personnel working in the facility from stray radiation. It is designed such that the dose limits applicable to these groups of persons cannot be exceeded under normal operation conditions and in case of accidents.

The shielding must guarantee that the dose rate in spaces accessible to the public does not exceed 0.5 $\mu Sv\ h^{-1}$, or 2.5 $\mu Sv\ h^{-1}$ in places without permanent occupancy (parking spaces, corridors, staircases, toilets...). In a supervised radiation area[1], such as the ISOLDE experimental area, the ambient dose equivalent rate is limited to 10 $\mu Sv\ h^{-1}$. Only locally, at inaccessible positions, higher values can be tolerated, but they must not affect the global average over the hall.

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[1] In the next revision of Safety Code F, « Protection against Ionising Radiation », the naming of designated radiation areas follows the conventions in France and other E.U. countries. The characteristics of the « supervised area » correpond largely to those of the presently defined «simple controlled radiation area ».

Line-of-sight shielding models [5] give a first, conservative estimate of expected dose equivalent H from the collision of high-energy protons with matter behind a shielding. Such models are based on a source term depending on proton beam energy and angle of radiation incidence $H_0(E, \theta)$, a $1/r^2$ - geometrical attenuation with total distance r and an exponential taking into account the radiation attenuation in a composite shield employing n different materials with thickness d_i and radiation mean free path lengths λ_i:

$$H(r,d) = H_0(E,\theta)\frac{1}{r^2}\exp\left(-\frac{d_1}{\lambda_1}-\cdots-\frac{d_n}{\lambda_n}\right)$$

The source term is calculated for an energy of E=1.4 GeV and a target for one mean free path length in which 63% of the protons will react. This choice is conservative even for the densest targets employing lead. It does not take into account the additional neutrons emitted from fission in U-C and Th-C targets.

Before 1990, all shielding were designed under the assumption that the average beam intensity at ISOLDE is 10^{13} protons s^{-1} at an energy of 1 GeV [4]. This corresponds to a current of 1.6 μA and a power of 1.6 kW, lower than presently used beam parameters. The ISOLDE target area has been shielded with concrete walls and earth shielding against areas accessible to the public (the parking spaces and the Route Democrite). The thickness of this shielding, resulting from the 1990 estimations, is equivalent to 8 m of earth. The weakest point of the shielding is situated at the emergency exit from Bat. 179 to Route Democrite, where ambient dose equivalent rates can temporarily exceed the guidance value of 2.5 μSv h^{-1} at present proton beam intensities.

Between the target area and the separator areas are approximately 4 m of earth shielding, reinforced by 0.8 – 1.2 m of iron. The separator areas are shielded against the experimental area by concrete blocks, with a thickness between 1 and 3 metres. Access mazes with a width of passage of 1 metre lead from the experimental area to the separator areas.

For the proposed HIE-ISOLDE beam with a current of 10 μA, the concrete and earth shielding around the target area becomes insufficient for protecting the public: in 10 m distance behind an earth shield of 8 m thickness, the expected ambient dose rate is 14 μSv h^{-1}, exceeding the relevant dose rate guidance value by a factor of 6.

For places in the experimental hall close to the shielding of the separator areas, ambient dose rates may reach 30 μSv h^{-1} (access door to HRS separator area) or 80 μSv h^{-1} (at the GHM or GLM beam line). These values exceed the guidance value for supervised radiation area by a factor of up to 8.

It is well known that neutrons stream from the target area into the High Voltage room and from there into the experimental hall. The HV room has been equipped with an access control system to protect personnel from the significant dose rates prevailing therein when uranium- or thorium targets are used. Today, the "sea" of neutrons in the experimental hall creates an ambient dose rate of 1 – 2 μSv h^{-1}, measured with the radiation monitors on the wall opposite the target area. A five-fold increase in beam power would increase the ambient dose rate to 10 μSv h^{-1} for the whole hall, leaving no margin for the extraction of radioactive beams into the experimental area.

In the controlled separator areas and the High-Voltage Room, radiation monitors are included in the interlock chain of the access control system. Access to the High-Voltage room is only authorised when the ambient dose rate there is lower than 100 μSv h^{-1}. At present beam intensities, this occurs during operation with U-C or Th-C targets on the HRS separator.

Once the proton beam is turned off, authorised personnel can access the separator areas when the ambient dose equivalent rate in these areas has dropped significantly below that of a high radiation area (2 mSv h^{-1}). Even then, careful planning of the work and optimisation of the radiation exposure are mandatory.

3 Activation in the Target Area and Dose to personnel

The personal dose limit at CERN is 20 mSv, but for the reason of ensuring the legally required optimisation of exposure, an action level of 6 mSv in one year has been set. This value of annual personal dose may only be exceeded in exceptional cases with a special authorisation. Installations at CERN must be planned and operated in such a way that a foreseeable excess of the action level under routine operation conditions is excluded.

The secondary particle cascade from the impact of the proton beam on the ISOLDE target is activating all materials in the target area. Radioactive contamination in and around the front-end constitutes an additional radiation source and exposed the personal to a contamination risk.

Today, the dose equivalent rate in the Faraday cages around the two production targets is typically $H^*(10) \approx 4 \ldots 5$ mSv h^{-1}. This ambient dose equivalent rate puts severe constraints on so-called “hands-on” maintenance of the target and the front-ends. Each intervention is carefully planned and closely monitored by RP personnel. Interventions in the target area are deferred towards the end of the annual shutdown in order to benefit from radioactive decay. These protective measures result in an annual collective dose for the ISOLDE target- and separator between 15 and 25 man-mSv. Today, annual personal doses to a few specialised individuals are in the range between 4 – 6 mSv and therefore very close to the action level. The procedure of exchanging a whole front-end, which is required whenever a major breakdown occurs, leads to a collective dose of 3 man-mSv.

Activation and contamination and thus the dose equivalent rate resulting from them are proportional to the number of protons hitting the targets. An increase of the number of protons by a factor of 5 would result in an ambient dose rate in the vicinity of the front-ends of up to $H^*(10) \approx 25$ mSv h^{-1}. If one simply scales the annual collective dose at HIE-ISOLDE with the same factor of 5, it would become comparable with that of the entire SPS.

It is obviously not possible to plan for a fivefold increase of activation and contamination and to continue with the present “hands-on” maintenance procedures, because it is foreseeable that the action level for annual personal dose would be exceeded. Consequently, the front-ends and the targets must be constructed in a way that urgent interventions during the running time of HIE-ISOLDE occur only very exceptionally and do not take more than fractions of minutes. Even towards the end of a 6-month long shutdown, ambient dose rates will be so high that maintenance of the whole target-front-end system must be reduced to the absolute minimum. A front-end change, for example, would lead to a collective dose of 15 man-mSv. This implies a redesign of the present target/front-end system, using manipulators and robots not only for changing targets but also for maintenance by changing whole functional groups of the front-end, when required.

4 Protection against Radioactive Contamination

Personnel working at ISOLDE are exposed to external radiation, as everywhere else in designated radiation areas at CERN. In addition, they risk being exposed to internal radiation after contamination with radioisotopes. The annual dose limit of 20 mSv and the action level of 6 mSv are understood as limiting the sum of external and internal exposure.

The isotopes produced in the ISOLDE targets present a risk of widespread contamination in the facility. The vacuum system in the target and separator areas is heavily contaminated. Past the switchyards, the contamination is becoming gradually weaker, but it cannot be neglected when intervening on the vacuum system in the experimental area. Turbo molecular pumps, backed up by oil-filled roughing pumps, maintain the vacuum. Radioactive isotopes are contaminating all vacuum pipes and the interior of the turbo molecular pumps, making standard maintenance impossible. The volatile isotopes are retained in the oil of the roughing pumps. These are installed at various places in the separator areas and the experimental area.

Depending on the type and concentration of isotopes captured in the oil, the pumps can have a significant dose rate (several mSv h^{-1} on contact). The annually required oil change exposes the personnel to a high contamination risk. The oil of the pump on the High Resolution Separator HRS contains 32 MBq of α-emitters (mainly $^{208, 209, 210}$Po). This corresponds to the 16 000-fold of the authorisation limit of these isotopes as defined in the Radiation Safety Code [1] in accordance with [2,6]. Extensive protective measures are required for this operation, which must be performed in a radioactive work sector of the highest protection class A [6].

Finally, the storage, conditioning and elimination of contaminated waste are more complicated and costly than for a comparable volume of activated waste. In the present layout, the HRS separator area (not classified as work sector of class A) houses several roughing pumps for the separators and front-ends. Changes of the layout of the experimental hall may result in installing more vacuum equipment in the separator areas.

In the separator areas, contamination risk occurs whenever the separators, switchyards and other beam line components are opened for maintenance. Due to the high ambient dose rates during operation ($H^*(10) > 100$ mSv h^{-1}), the separator areas are presently classified as primary accelerator areas. There is no physically tight separation between them and the experimental area, permitting free exchange of air-borne contaminants during maintenance or in case of failure. Some control equipment is installed in one separator area, exposing its maintenance personnel to external and potentially internal radiation.

Interventions in areas with high dose rates with the risk of personnel contamination require thorough job- and dose planning and the close supervision by RP personnel. At present, one RP engineer is delegated for work at ISOLDE, for difficult interventions he receives backup by another engineer. On average, 1.5 FTE of RP personnel are monitoring work at ISOLDE.

While optimisation of radiation protection at the present ISOLDE facility would benefit from a strict separation of the different areas (target-, separator-, vacuum- and experimental), this will become indispensable for the increased contamination risk in HIE-ISOLDE.

With a contamination of α-emitters at the 100000-fold of the authorisation limit, the standard operation of changing the pump oil requires additional protective measures against contamination and external radiation for the maintenance personnel. Other personnel must be protected from external and internal exposure by the vacuum system. All potentially contaminated vacuum equipment, including that from the experimental area, should be grouped in a shielded work sector of class A exclusively reserved for vacuum applications.

The separator areas shall be freed from all indispensable equipment, classified as a radioactive work sector, at least during maintenance operation, and properly isolated from the experimental area.

The ISOLDE (and HIE-ISOLDE) experimental area is provisionally classified as a work sector of class C [6] although the building does not fulfil the required fire resistance requirements for such an area. The activity which can be manipulated in unsealed form in the hall is limited to the 100-fold of the authorisation limit. This limitation allows conducting experiments with reasonable amounts of gamma/beta emitters. Use of short-lived gamma/beta emitters may be limited by the ambient dose rate they create in the experimental hall, and which is limited to 10 μSv h^{-1}. The s availability of unsealed alpha-emitters for experiments is seriously limited by their low authorisation limit. The benefit from an increased production rate will be marginal for experiments relying on collected radioisotopes in unsealed form or on short-lived gamma/beta emitters because of the limitations of the experimental area.

An overall increase of the risk of external and internal irradiation calls for increased efforts of the Radiation Protection Group for monitoring, planning and supervision of work at HIE-ISOLDE.

The increased risk demands also a review of the practice to allow control of the mass separator to CERN users. The around-the-clock presence of operators in a HIE-ISOLDE facility with fivefold increased proton current would greatly benefit operational safety.

5 Radioactive Releases from ISOLDE

The annual dose limit for the public from air releases is 300 μSv for the whole of CERN [1]. In Switzerland, no further optimisation efforts are required once members of the public are exposed to less than 10 μSv a^{-1} [1,2]. It is considered good practice at CERN not to exceed this constraint for gaseous releases. For comparison, exposure of the public from releases from nuclear power plants in Switzerland is between 1 and 5 μSv a^{-1}. In 2004, air releases from TT10 contributed 1.3 μSv to the dose to members of the public. This value will increase with the operation of the CNGS beam, a first, conservative estimate for 4.5 10^{19} protons on the CNGS target indicates an annual dose of 5.3 μSv. The unrestricted running of all experimental facilities on the Meyrin site will call for technical solutions to reduce releases and the dose to the public.

For assessing the impact of radioactive releases on the environment and the public, CERN implements the usual approach to estimate the dose to a member of the "critical group" of the public. The critical group is defined such that the impact of releases from CERN is maximised (by age, by the place of residence or work and by living habits). If the dose to the critical group is not exceeding limits and can be shown to be optimised, this will be true for an arbitrary member of the public. The calculation of dose to a member of the critical group follows regulations from the competent authorities in the host states [7].

There are three types of radioactive gaseous releases from ISOLDE:

1. The release of mainly short-lived positron emitters (^{11}C, ^{13}N...) and ^{7}Be. They are produced via the spallation reaction by the secondary particle cascade resulting from the 1.4 GeV proton beam hitting the target. During operation of ISOLDE, these gases are emitted continuously via the ventilation system.
2. The release of spallation products produced in the ISOLDE targets via the vacuum system of the separators and the experimental hall. Tritium and long-lived noble gases (^{42}Ar, ^{85}Kr and ^{127}Xe) are not retained in the roughing pump oil of the vacuum system. These gases are stored in retention tanks and released after allowing for 5 – 12 months for radioactive decay. The retention tanks are placed in the ISOLDE target area and they have become activated, making an assessment of their activity contained in them by an external dose rate measurement impossible. The tanks are filled up to a positive pressure of 2000 hpa, forcing radioactive gases out in case of a leak.
3. The short-term release of $^{219,\ 220}$Rn and its decay products $^{211,\ 212}$Pb and of iodine isotopes during the change of U-C and Th-C targets.

In a nuclear or accelerator facility it is standard practice to release activated air via a filtered and monitored stack. The filters will retain most aerosols (notably ^{7}Be) and the monitors will allow quantifying the releases and demonstrating that no limits are exceeded and that the operation of the facility is optimised.

The ISOLDE stack constructed in 1990 was too short to allow for complete mixing of the released air and did not permit reliable release measurement. During the shutdown 2004/5, the ISOLDE facility has been equipped with a new, longer stack. This stack guarantees a laminar flow pattern, the prerequisite for an accurate airflow measurement and a representative air sampling. Reliable figures on the release of short-lived β^+-emitters will be available during 2005. Only then it will be possible to estimate the consequence of an increase of beam power by simple scaling.

At constant beam energy, the production of short-lived β^+-emitters from spallation in air will increase proportionally to the beam current. It may become necessary to significantly modify the ventilation and release system to cope with increased air activation.

For the spallation products from the target, the proportionality to release is mitigated by the decay time, but for the long-lived isotopes of noble gases in the retention tanks the final result will remain approximately proportional to beam power.

The impact of the releases from the retention tanks is monitored by streaming the gas through a monitor chamber. There is no sampling bias involved. The calculated dose to the critical group of the public is negligibly small compared to the short-lived β^+ emitters. As long as the retention tanks are sufficiently dimensioned to allow storing radioactive gases for sufficient decay time, releases will not represent a problem. At the increased production rates of radioactive gases at HIE-ISOLDE, the retention tanks should allow external monitoring of the contained activity and they should be inherently safe against leakage, as for example at SPIRAL in GANIL [10].

The Rn-emanations from target and front-end during target changes must be reduced by an appropriate design of new targets and front-ends.

A second pathway of activity releases is water. Rainwater infiltrates the earth shielding over the ISOLDE area, may be activated and contaminated, and reaches the drainage system of CERN or may reach the ground water. Moisture of unknown origin is regularly observed in the target area. The source of the moisture may be in communication with drainage or ground water. Before increasing beam intensity and activation levels, a sampling pit shall be installed in the vicinity of the ISOLDE target area; permitting regular controls the of the water activation. The water from the ISOLDE facility is drained towards the CERN outlet "Car Club" and discharged into the river Nant d'Avril (CH).

6 Production and elimination of radioactive waste

Radioactive waste is defined as activated or contaminated material or equipment for which no further use is foreseen and which can be disposed of. Legislation and reglementation in the host states impose a strict control over radioactive waste. Only under well-defined technical and administrative conditions may radioactive waste be released for reuse, for example as scrap metal. CERN disposes of intermediate storage space for radioactive waste. A treatment- and conditioning centre is in preparation. There, radioactive waste will be prepared for the definitive transport to radioactive waste repositories in the host states.

It is CERN policy that the producer of radioactive waste bears the cost of its elimination [1].

In contrast to most radioactive waste from other accelerators at CERN, waste from ISOLDE generally presents a substantial contamination risk. For the risk of external and internal exposure from ISOLDE waste, the same remarks as in chapter 3 and 4 are applicable. At the end of the annual shutdown, about 30 spent targets are transported to a provisional storage area in the ISR, where they await their elimination from CERN. The storage area for targets has 350 places; it is presently saturated and cannot be extended in the foreseeable future. A project has started in AB department and the Safety Commission to define the necessary tools and procedures for characterisation, conditioning and transport of the targets to the Federal Intermediate Storage Centre (Bundeszwischenlager BZL), located at the Paul-Scherrer Institute PSI in Villigen, Switzerland.

The aim of HIE-ISOLDE is an increased production of radioisotopes for research purposes. This will go hand-in-hand with a proportional increase in the production of radioactive waste, in particular spent targets.

After an increase of proton beam current, the total activity declared as waste would increase proportionally. This will have consequences for the tools and procedures for waste conditioning at CERN. It will also have an influence on the price of elimination, which is determined by the volume of the waste. However, the waste volume cannot be reduced arbitrarily (e.g. by super compaction), because of additional limits on total alpha activity per storage container. Two limiting cases can be envisaged:

1. The lifetime of the targets is related to the total number of protons received. The present lifetime limit is approximately 10^{19} protons. If the targets remain unaltered, the proton beam increase would result in an important increase in the volume of waste (up to a factor of 5), with the same activity per target. This amount cannot be handled either in the facilities envisaged for the

elimination project nor by the personnel available in either AB or SC department.

2. If the target lifetime would be increased, the result could be the storage of targets containing up to 5 times more activity than at present. This will impose longer waiting times before and improved protective measures during pre-conditioning operations. All installations and procedures envisaged in the project for target elimination should be designed with these consequences from a beam current increase in mind.

In either case, a new provisional storage area with the necessary protective measures against contamination needs to be provided at CERN for ISOLDE targets.
Finally, an increase of proton current will lead to higher activation levels in the whole HIE-ISOLDE facility. Final dismantling, conditioning and storage of parts or the whole of this facility will become more complicated and costly and the necessary funds for this must already be foreseen in the CERN budget.

7 Summary and Conclusions

The proposed increase of proton beam current in the HIE-ISOLDE facility will make the current provisions for radiation protection inadequate. Their necessary upgrade will require numerous modifications to the existing facility, new and improved work procedures and additional staff in the areas of

- Shielding and access
- Optimisation of external irradiation
- Protection against contamination
- Optimisation of releases into the environment
- Storage and conditioning of radioactive waste.

All items in this list must be addressed during the planning stage of HIE-ISOLDE in order to define technical and manpower solutions. Only after this evaluation, the approximate financial cost for improvements and additional staff can be reliably estimated.

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9 References

[1] Safety Code F, Protection against Ionising Radiations, Revision 1996, CERN (1996) under revision

[2] Ordonnance sur la radioprotection (ORaP du 22 juin 1994 (Etat le 4 avril 2000) 814.501, Switzerland (2000)

[3] D. Forkel-Wirth, A. Muller, F. Pirotte, *First Safety Study on the Production of Radioactive Beams at ISOLDE by Using the Proton Beam of SPL*, CERN-SC-2005-TN-030 (2000)

[4] A.H. Sullivan, *Radiation Safety at ISOLDE,* CERN/TIS/RP/93-13 (1993)

[5] A. H. Sullivan, *A Guide to Radiation and Radioactivity Levels Near High Energy particle Accelerators*, Nuclear Technology Publishing (Ashford, England) (1992)
[6] Ordonnance sur l'utilisation des sources radioactives non-scellées du 21 novembre 1997 (Etat 23 décembre 1997), 814.554, Switzerland (1997)
[7] P. Vojtyla, Models for Assessment of the environmental impact of Radioactive Releases from CERN Facilities, CERN-TIS-2002-013-TE (2002);
[8] L. Moritz, *Radiation safety at ISAC,* in: T. Kehrer, P. Thirolf (eds.) *Workshop on Radiation Protedction Issues Related to radioactive Ion-Beam Facilities (SAFERIB)*, CERN 30.10.-1.11. 2002, CERN-2003-004 (2003)
[9] P. Vojtyla, SC-IE, Private communication March 2005.
[10] P. Jardin and the Ion production group , *Management of Radioactive Gases at the SPIRAL facility*, in: T. Kehrer, P. Thirolf (eds.) *Workshop on Radiation Protedction Issues Related to radioactive Ion-Beam Facilities (SAFERIB)*, CERN 30.10.-1.11. 2002, CERN-2003-004 (2003)