Radiation protection study for the HIE-ISOLDE project at CERN

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Abstract

The HIE-ISOLDE project will expand the physics programme at the ISOLDE Facility at CERN with the possibility to post-accelerate a large variety of radioactive ion beams to energies well below and significantly above the Coulomb barrier. While this project contains three major elements: higher energies, improvements in beam quality and higher beam intensities, the most significant improvement is the replacement of the current post-accelerator (REX) by a new superconducting linear accelerator delivering ions of energy up to 10 MeV/u. This energy upgrade leads to new radiological hazards such as neutron emission when the post-accelerated beams at energies above the Coulomb barrier interact with beam intercepting devices or the vacuum chamber walls in case of beam loss. The new superconducting cavities installed will also be a strong source of X-rays due to electron field emission.

A review of the operating parameters of similar facilities allowed us to conclude that X-rays emitted by the cavities would drive the shielding requirements for the post-accelerator. In this context, systematic measurements of the X-ray levels were performed during RF cavity tests to evaluate the radiation source term. FLUKA simulations allowed the assessment of shielding requirements and geometry of the tunnel hosting the superconducting cavities, as well as evaluation of the maximum neutron dose rates expected in the event of beam losses. Activation of the machine components was also estimated, allowing the determination of the future waste classification due to beam-induced activation.

Introduction

The ISOLDE Facility at CERN is mainly dedicated to nuclear physics studies. At ISOLDE, Radioactive Ion Beams (RIB) are produced and post-accelerated up to 3 MeV/u. The HIE-ISOLDE (High Intensity and Energy ISOLDE) project will expand the nuclear physics programme at the ISOLDE Facility at CERN, by upgrading the ion beam energy and intensity, as well as the beam quality. New radiological hazards are expected after the energy upgrade of the facility, which require new mitigation measures to be integrated in the project.

In the first part of this paper, the HIE-ISOLDE Facility is presented, as well as radiation protection hazards related to the future post-accelerator. The procedure followed to determine the radiation source term, by comparison to similar facility and through X-ray measurements, is then described. The results of FLUKA simulations for X-ray dose rates, neutron emission due to beam losses and material activation are also reported. The technical shielding design chosen and the different mitigation measures required to deal with the different radiological hazards are presented.

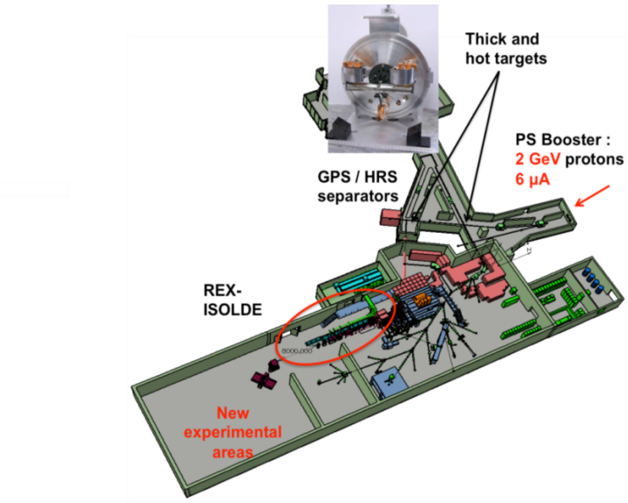
The HIE-ISOLDE project at CERN

HIE-ISOLDE is a project aiming to improve the performances and capabilities of the ISOLDE Facility at CERN with an increase in the accelerated beam energy and intensity as well as with an improvement of the beam quality. The installation of the necessary hardware will take place in three stages between 2014 and 2018.

The ISOLDE Facility

The current ISOLDE Facility [1] allows RIBs with masses ranging from He to U to be produced and accelerated at energies ranging from 300 keV/u to 3 MeV/u. The proton beam delivered by the PS Booster (PSB) with an energy of 1 or 1.4 GeV and an intensity of 2 μA is used to produce spallation, fragmentation or fission reactions in the ISOLDE target. The radioactive ions are then extracted by diffusion and by ionisation processes. The General Purpose Separator (GPS) and the High Resolution Separator (HRS) allow the isotopic separation, selection and distribution of the beam to the experimental areas. The presence of a post-accelerator in one of the experimental beam line allows RIBs to be accelerated up to 3 MeV/u.

Figure 1. General layout of the ISOLDE experimental hall



The HIE-ISOLDE upgrade

The HIE-ISOLDE project consists of three different upgrades of the facility [2]. First, the intensity upgrade is related to the replacement of PSB injector, linac2, by linac4 (~ 2017) and the energy increase of the PSB from 1.4 GeV to 2.0 GeV. Following this upgrade, proton beams received at ISOLDE will reach 2 GeV and 6 μA on ISOLDE production targets, which requires a completely new target design and the consolidation of the ISOLDE target area [3]. Second, due to a new RFQ cooler and buncher, a better mass resolving power to select the ions of interest for the experiments will be achieved, improving the ion beam quality. Finally, the most significant upgrade of the facility is the replacement of the existing Radioactive ion beam EXperiment (REX) linac by a superconducting linac consisting of 32 superconducting cavities. It will allow the ion beam to be accelerated up to 10 MeV/u, which is above the Coulomb barrier for most target/projectile combinations. The new radiation hazards introduced by the replacement of the post-accelerator are studied in this paper.

Radiation protection issues in the experimental hall

Radiation protection hazards

The different radioactive hazards associated with the construction of a new post-accelerator are the risks due to the implanted radioactive or volatile radioactive ions, the X-ray emitted by the superconducting RF cavities or the prompt neutron dose when the beam impinges on a target along its path.

The use of RIB involves a risk of external exposure: beam losses in normal operation of the machine may lead to the build-up of strong gamma-ray emitters (e.g. ^{7}Be, ^{74}As, ^{88}Y, ^{121}Te, ^{125}I…) in the vacuum pipe or vacuum chamber. Moreover, the production of volatile radiotoxic isotopes represents a risk of internal exposure during intervention requiring the opening of the vacuum chamber, in particular by alpha-emitters (e.g. ^{148}Gd, Po, daughters of ^{228}Ra/Th, etc.). As these risks already exist at ISOLDE, the same precautionary measures will apply at HIE-ISOLDE: beam intensity reduction and expiration duration limitation during isotopic collection, gamma monitoring and RP supervision and the use of appropriate protective equipment while opening vacuum chambers.

The replacement of the REX-ISOLDE post-accelerator by a new superconducting linac made of 32 superconducting RF cavities involves the emission of X-rays. These cavities are made of Cu and covered by a thin Nb deposit [5]. During the sputtering process, defects or dust can appear at the surface of the cavity, which will emit electrons during RF operation. These electrons, accelerated by the accelerating field, lead to bremsstrahlung X rays. However, as the intensity of X-rays emitted depends on the cleanliness and surface state of the cavity, measurements are required to evaluate expected dose rates during operation.

The possibility of accelerating ions above the Coulomb barrier induces the possibility of neutrons being produced during beam losses. The intensities expected for characteristic RIB used for experiments and stable beams used for beam tuning are presented in Table 1.

Table 1. Characteristic ion beam intensities at HIE-ISOLDE [4]

Beams	A/Q	Energy (MeV/u)	Intensity (ppA[1])	Comment
RIB	2	19.8	< 1	RIB (limit case)
Ne5+	4	11.3	1	Stable pilot beam
N4+	3.5	12.6	5	Stable pilot beam
He2+	2	19.8	10	Stable pilot beam
Ne5+	4	11.3	200	High intensity stable beam

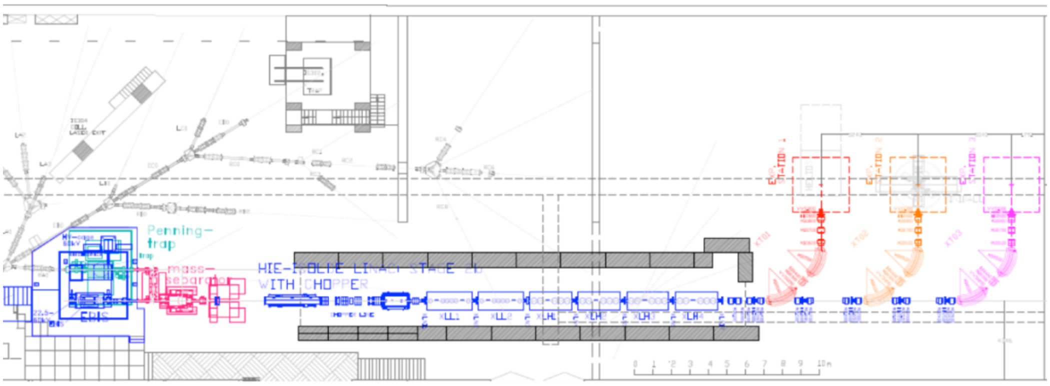
In order to evaluate the main radiological hazards, HIE-ISOLDE was compared to similar facilities such as ISAC2 in TRIUMF (RIB accelerated up to few pnA intensity) [6] and ALPI in Legnaro (stable ion beams) [7], which both use superconducting accelerating structures. The HIE-ISOLDE intensity is lower by a factor 100 to 1000 as compared to ISAC2, while neutron dose rates due to ion beam losses are expected to be below 1 µSv/h. Since X-ray dose rates emitted by superconducting cavities measured at ALPI reached up 360 mSv/h at contact [8], X-rays are the main hazards at HIE-ISOLDE.

1 ppA: particle pico-ampere; 1 ppA is equivalent to 6.25 10^{6} particles/s.

Constraints and challenges

The main constraint of the HIE-ISOLDE post-accelerator is its location in the experimental hall, close to experimental area and users (see Figure 2). In order to keep the current classification of the experimental hall as supervised radiation area (ambient dose rate below 3 µSv/h for permanent workplaces), a shielded enclosure will be built around the future post-accelerator. The design objective for parasitic X-rays was set to 1 µSv/h behind the shielding.

Figure 2. Location of the HIE-ISOLDE post-accelerator in the experimental hall close to experimental areas



In addition, several penetrations in the bulk shielding are needed to integrate the required services to the post-accelerator, such as high voltage, RF, He supply and exhaust. In order to comply with these constraints, the shielding was designed in close collaboration with the team in charge of civil engineering.

The main challenge for the specification of the shielding was the definition of the source term. The bremsstrahlung X-rays come from electrons removed from the defects of the cavity, which are accelerated and hit the cavity surface during RF operation. Since this emission depends on the surface state of the cavity, no theoretical and systematic source term can be derived and direct measurements are required to determine the X-ray intensity emitted by the cavities.

Source term evaluation: X-ray measurements and FLUKA simulations

X-ray dose rates have been measured on contact with the cryostat during RF tests on several prototype cavities, using a 30 cm^3-ionisation chamber placed at the height of the beam pipe. The Monte Carlo code FLUKA [9,10] was then used to perform simulations of the cavity test bench, allowing the determination of the rate at which electrons are removed from the cavity surface.

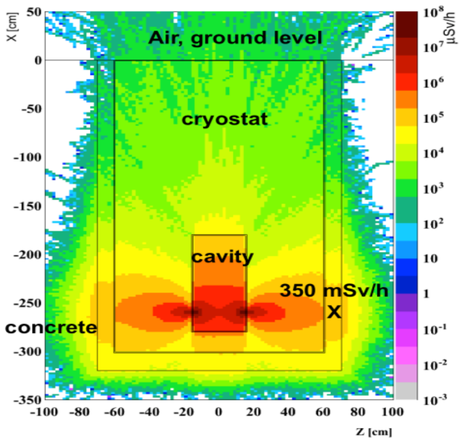
There are three different modes of operation for RF cavities. The first one is quality factor measurement, corresponding to normal operation of the accelerator. The second is "normal" conditioning, preliminary step to normal operation, which consists of the excitation of the cavity by a strong RF power to overcome the multipactor barrier. The last mode of operation, called He processing, is a specific conditioning where He is sent to the cavity and transformed into plasma after excitation by a strong RF power [12]. This procedure allows emission sites to be cleaned and removed, but involves the emission of a large amount of X-rays. The maximum dose rates measured during RF tests for these three modes of operation are presented in Table 2. The maximum dose rate was measured during He processing and reached 350 mGy/h. Weighting factors for electrons and X rays being wR=1, a source term of 350 mSv/h was used for shielding calculations.

Table 2. Maximum dose rates measured on contact with the cryostat contact at the beam pipe level [11]

Beams	Normal operation	Standard conditioning	Conditioning by He processing
Maximum dose rate measured at cryostat contact (mGy/h)	20	20	350

In order to evaluate the electron removal rate, dose rates around the cryostat were simulated with FLUKA. Considering the maximum RF field strength and the length of the cavitiy, the maximum energy that a parasitic electron can reach in a HIE-ISOLDE cavity is 900 keV. In order to be conservative, it was considered that all the electrons reach an energy of 900 keV. Using the measured dose rate level of 350 mSv/h at the position of the ionisation chamber, the electron emission rate could be derived. This intensity for one cavity, 1.5e14 e-/s, was later used to normalise FLUKA simulations of the post-accelerator (see Radiation Protection study, X dose rates). The results of the simulation for the test area cryostat with a single cavity are presented in Figure 3.

Figure 3. Simulation of dose rate distribution around the cryostat during RF tests



Radiation protection study

As a first step, the bulk shielding was determined using the measured dose rate levels and the attenuation coefficient for 900 keV photons. Then, FLUKA simulations were performed to validate the shielding thicknesses and identify possible weak points considering the different openings and chicanes required for services (RF, HV, He supply, etc.) integration. The dose rate levels in the vicinity of the beam line due to the ion beam interaction were also evaluated. Finally, residual dose rates and material activation were also estimated with consideration of the very short cooling time after operation.

Shielding thickness evaluation

The shielding thickness was first determined analytically, using Equation (1):

$$x = \frac{\ln(H_0/H^*(10))}{\ln 10} x_{1/10} \qquad (1)$$

where $H_0$is the equivalent dose rate before attenuation, $H^*(10)$ the equivalent dose rate after attenuation and $x_{1/10}$ the tenth-value layer for a given material in cm[-1]. The source term H_0 was evaluated to 350 mSv/h and the target design value was fixed to $H^*(10) = 1\ \mu Sv/h$ for X-rays. The equivalent thicknesses obtained for different shielding materials are given in Table 3.

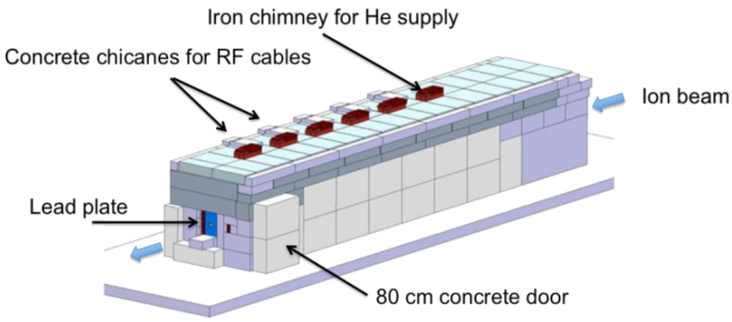
Table 3. Equivalent shielding thicknesses for different materials

Beams	Concrete	Iron	Lead
Thickness (cm)	80.5	26.8	13.4

FLUKA simulations

The HIE-ISOLDE post-accelerator geometry was implemented in FLUKA as 6 stainless-steel cryomodules containing each 5 low-beta or 6 high-beta cupper cavities. Shielding geometry has been defined in close collaboration with the team in charge of service integration. The bulk shielding is 80 cm concrete. Chicanes have been implemented on the concrete roof for RF cables, as well as in iron chimneys to reduce the dose rates expected on the top of the shielding. However, some cables cannot be bent and some vertical penetrations go straight through the shielding. A general view of the shielded enclosure is presented in Figure 4.

Figure 4. Shielding geometry of the future HIE-ISOLDE post-accelerator

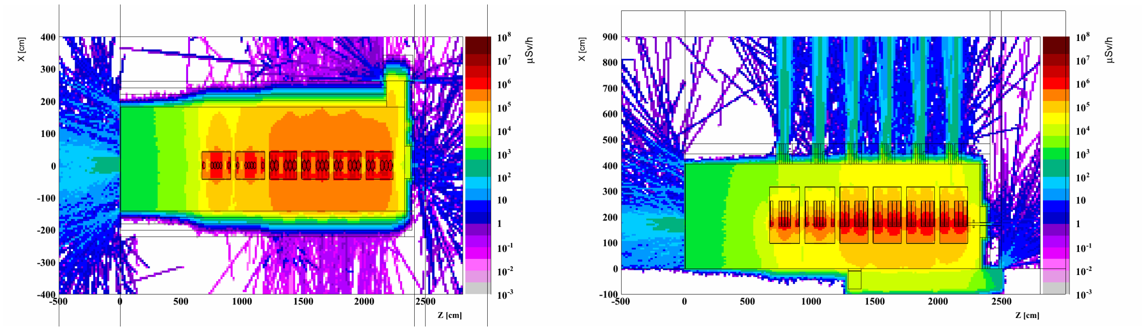


X-ray dose rates

For X-ray dose rates calculations, 32 electron emission sites distributed in each cavity with the maximum possible energy (600 keV for low-beta cavities and 900 keV for high-beta cavities) were used as primary particles (see Figure 5). The electron emission rate considered was deduced from measurements and simulations of the test cryostat (see Source term evaluation) considering the He processing phase, which is our worst-case scenario. While the 32 cavities are considered in this study, in practice only a single cryomodule (6 cavities maximum) should be conditioned at the same time. Moreover, this operation will take place only once a year for a few days. During normal operation or normal conditioning, dose rates are expected to be at least 10 times lower.

Inside the tunnel, dose rates can reach up to 300 mSv/h between two cryomodules and 30 mSv/h on top of a cryomodule during He processing of the whole post-accelerator. Outside the bulk shielding (accessible areas), the target design value of 1 µSv/h is achieved (see Figure 5, right). Due to the many penetrations on the roof of the shielding, dose rates out of chimneys reach up to 300 µSv/h (see Figure 5, left). As a consequence, access to the roof will be forbidden during RF operation, unless acceptable dose rates are measured during operation.

Figure 5. Dose rate distribution around the post-accelerator during He processing; (left) horizontal cut at beam height; (right) vertical cut at beam position

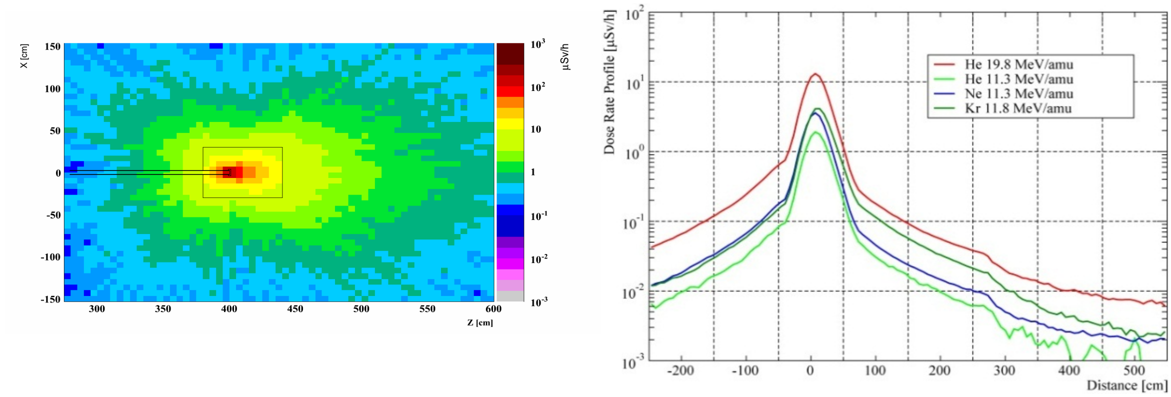


Neutron dose rates from ion beam losses

To estimate neutron dose rates expected in the event of ion beam losses due to beam intercepting devices, FLUKA simulations were performed for the most constraining case of stable beams during machine settings. Both losses in a beam dump and losses at a grazing angle in a magnet vacuum chamber were considered, but only the first study is presented here, as the results obtained were similar.

Dose rate distribution around a Cu dump irradiated by a-11.3-MeV Ne^{5+} beam with an intensity of 4 ppA is presented in Figure 6 (left). At 1 m and 90 degrees from the beam dump, dose rate is a few µSv/h. The case of He at 19.8 MeV/u presented in Figure 6 (right) is a very specific case and will be authorised with additional mitigation measures. For beam settings with intensity leading to dose rates higher than few µSv/h at 1 m and 90 degrees of a beam intercepting devices, small exclusion areas will be implemented around the beam loss point during the duration of the tuning period.

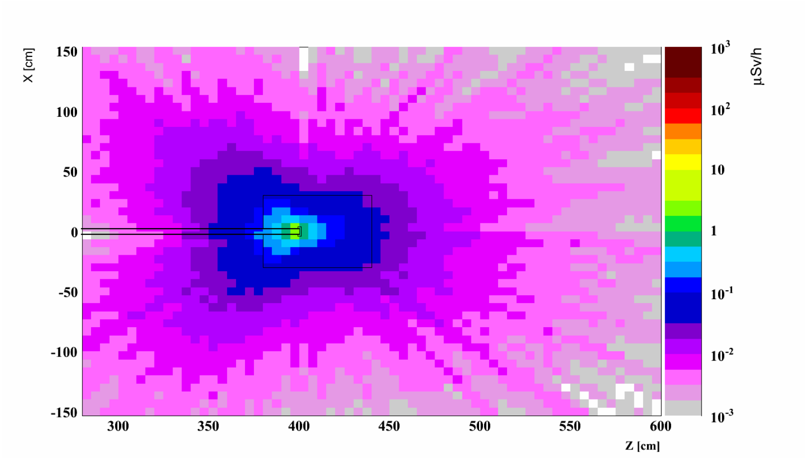
Figure 6. Dose rate distribution for a 11.3 MeV Ne beam impinging on a copper dump (left) and dose rate profiles at 1 m and 90 degrees for 1 ppA ion beams (right) in the event of a total ion beam loss



Residual dose rates

Residual dose rates due to ion beam losses have been estimated around a Cu beam dump and a magnet after different of cooling times at the end of the use period of the post-accelerator. As shown in Figure 7, residual dose rate distribution after 1s cooling time around the beam dump is already well below 1 µSv/h at 40 cm from the dump.

Figure 7. Residual dose rate around a beam dump after one-second cooling time



Material activation and radioactive waste

The radionuclide inventory has been calculated after 30 years of operation and one year of cooling time for a Cu beam dump and a magnet, considering a total beam loss during the whole period. The case of a loss occurring in a dipole magnet is presented here. The magnet coil is made of copper cooled with demineralised water and the yoke of iron. The activities after one year of cooling time of the radionuclides produced in copper and iron are shown in Table 4 and compared with the exemption limits used at CERN for the design of new facilities [13]. The design limits are conservative as compared to the ones specified in the corresponding Swiss legislation [14]. As a mixture of radionuclides is present in material activated during accelerator operation, the following sum rule [12] [13]:

$$\sum_{i=1}^{n} A_i/LE_i < 1$$

applies (with A_i the activities of the radionuclides of artificial origin and LE_i the corresponding exemption limits). Following the sum rule, materials containing a specific radionuclide activity of artificial origin smaller than one are exempted from further regulatory control. This is the case for irradiated materials at HIE-ISOLDE, as presented in Table 4. In addition, it was also concluded that no radionuclides produced in circulating cooling water or water activation are expected in HIE-ISOLDE magnets. The same conclusion was drawn for the beam dump study. As a consequence, activation of beam line components during beam tuning period or physics is considered negligible and the waste characterisation after the facility decommissioning will depend on the implantation of RIBs in the concerned equipment.

Table 4. Dipole activation after 30 years of operation and one-year cooling time

Material	Nuclide	$T_{1/2}$	LE_i (Bq)	A_i (Bq)	A_i / LE_i	$\sum_{i-=1}^{n} \frac{A_i}{LE_i}$
Copper	^{63}Ni	100.1 y	7E+04	1.9E+01 ± 1.35%	2.7E-04	1.19E-01
	^{60}Co	5.3 y	1E+02	1.1E+01 ± 3.58%	1.1E-01	
	^{3}H	12.3 y	1E+05	5.0E-01 ± 13.71%	5.0E-06	
Iron	^{55}Fe	2.7 y	3E+04	7.9E+01 ± 1.24%	2.6E-03	1.30E-01
	^{54}Mn	312.5 d	1E+02	1.3E+01 ± 2.14%	1.3E-01	

Conclusion

The first step of the HIE-ISOLDE, which corresponds to the energy increase of the post-accelerated beam delivered by the ISOLDE Facility at CERN, is underway and will allow new opportunities for nuclear physics experiments. However, the energy upgrade, allowing beams to be accelerated above the Coulomb barrier and consisting of the replacement of the REX post-accelerator by a superconducting linac, involves new radiological hazards such as neutron and X-ray emission.

After the identification of X-rays as the main radiological hazards of the future post-accelerator by comparison with similar facilities, a radiation source term of 350 mSv/h at 1.4e14 pps (electron) was derived from measurements and FLUKA simulations. Then, FLUKA simulations validated shielding thickness and design by considering the worst-case scenario for radiation emissions (maximum electron energy, He conditioning of all cavities at the same time). In that configuration, no access will be authorised on the roof of the shielding during RF operation. The concrete shielding blocks have already been installed in the HIE-ISOLDE experimental hall.

In the event of energy loss during machine tuning with stable ion beams, dose rates could locally reach values above the limit. Small exclusion limits around the beam intercepting devices should be installed during that short period of time.

No specific measures concerning residual dose rates due to beam induced activation are necessary, as the expected dose rates 1s after cooling are already at background levels due to the low beam intensity. Activation of material after 30 years of operation should be negligible 1 year after cooling time, and no water or air activation is expected.

Acknowledgements

A Marie Curie Early Training Network Fellowship of the European Community's Seventh Programme under contract number PITN-GA-2010-264330-CATHI has supported this research project. Thanks are due to the HIE-ISOLDE collaboration at CERN and external partners such as TRIUMF and INFN Legnaro for supporting this study.

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