CHALLENGES FOR RADIATION PROTECTION AT FUTURE ISOTOPE PRODUCTION FACILITIES

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Accelerated beams of exotic, unstable isotopes of increasing intensity are essential tools for current research in Nuclear Physics and Astrophysics. In order to be able to deliver these beams, studies for a next generation of isotope production facilities are in progress in Europe, Asia and North America. The exotic isotopes would be produced in spallation targets, driven by proton or heavy ion accelerators with a kinetic energy of around 1 GeV/u and beam currents between 100 μA and several mA. The major challenges for radiation protection at these facilities are the protection from radiation from the high-power production targets, dissipating between 100 kW and several MW of beam power, and the management of the radioactive inventory of the targets during use, maintenance and disposal. In the case of the European project EURISOL, which intends to employ a Uranium-Carbide fission target, safeguarding the produced actinides is a specific issue.

I. INTRODUCTION

Fundamental research in nuclear physics experienced a renaissance in the 90's of the last century thanks to the availability of accelerated, radioactive ion beams (RIB) of high purity and reasonable intensity. Facilities such as CYCLONE (Lovain-la-Neuve, Belgium), SPIRAL (Caen, France) and REX-ISOLDE (CERN, Switzerland/France) were paving the way of this line of research in Europe. They supply radioactive ion beams to a large user community from nuclear structure physics, astrophysics, solid state physics and the life sciences. The principle of operation of these installations is the production of radioactive nuclides by an intense, high-energy proton or ion beam in a target via spallation- or fission reactions. The radionuclides diffuse out of the production target; they are ionized and then extracted by a high-voltage electrode. The radioactive ions are then transported at relatively low energy (30 – 60 keV) to experimental stations, or they are "bred" to a higher charge state and accelerated in a post-accelerator to energies of a few MeV per nucleon.

A European Road Map for radioactive RIB facilities sets out from the successful installations of today, operating at beam powers of not more than a few kW. In an intermediate step, the existing facilities would be extended and upgraded, having beam powers in the range between 10 and 100 kW and post-accelerators with terminal energies of (10 - 20) MeV/u. The ultimate stage of the European Roadmap is the EURISOL facility, where several production targets would operate in parallel, with beam powers between 100 kW and up to 4 MW. The post-accelerator coupled to these targets might reach the range of 150 MeV/u. It is expected, that this facility could supply radioactive ion beams which are 1000 times more intense than today to the users. This will open new windows on all areas of nuclear research which are out of reach of present-day technologies because of exceedingly small cross sections for production or interaction.

This paper discusses a few of the challenges that future RIB facilities, with significantly higher beam powers and radioactive beam intensities, will have for radiation protection. The EURISOL project is taken as an example for projected similar RIB facilities on other continents. While the design of different planned facilities may vary, the challenges for radiation protection are largely similar

In section 2, the EURISOL facility is briefly described. Chapters 3, 4 and 5 discuss in more detail the radiation protection issues arising in the driver beam, the isotope production target and in the beam-handling and experimental areas. Finally, Chapter 6 is a summary of the most important findings.

II. The EURISOL FACILITY

EURISOL is a collaboration of European institutions with the aim to design, build and operate a next-generation radioactive ion beam facility in Europe[1]. The EURISOL study was supported financially by the European Commission in the 5th framework program. Presently, the EURISOL design study is supported in the 6th framework program. 20 institutions from 16 countries are contributing to the design study. One of the 12 work packages in the design study deals explicitly with questions of radiation protection.

Schematically, the EURISOL facility consists of a drive beam linear accelerator (linac), supplying proton- or light ion beams with a beam power of up to 4 MW, the isotope production targets, a beam preparation area with mass separators and charge breeders, a post-accelerator and experimental areas (Figure 1).

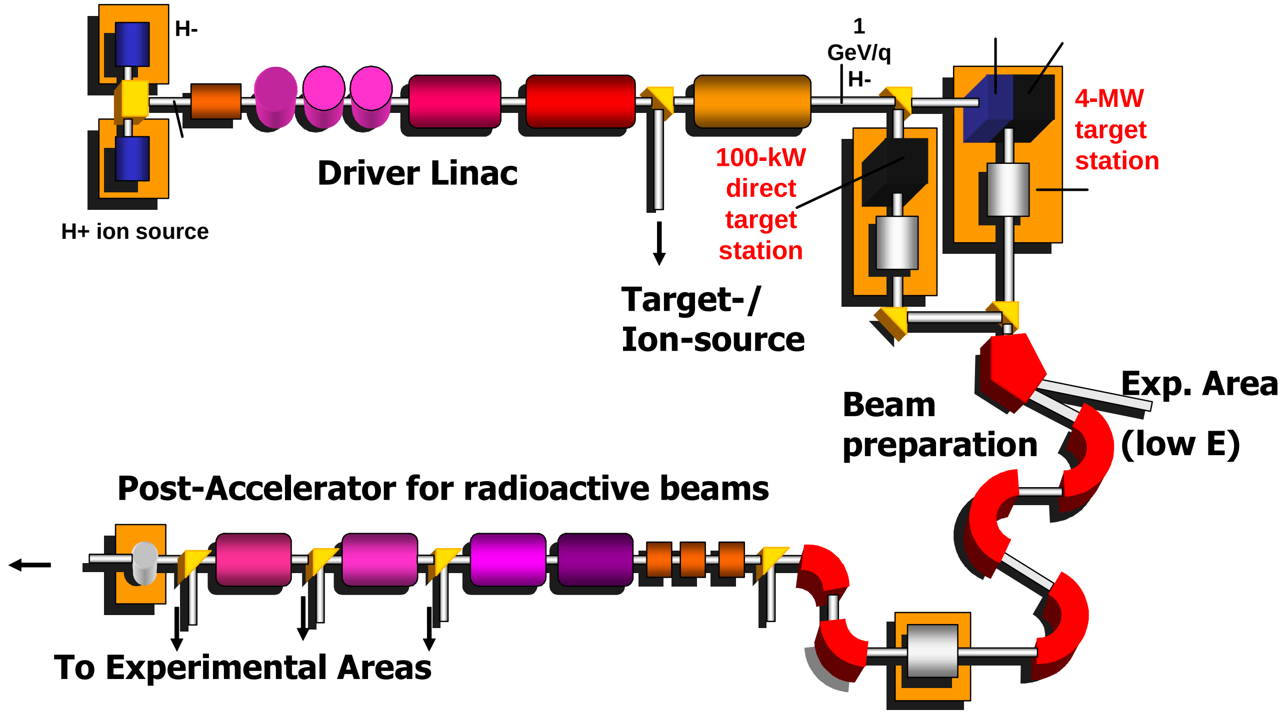

Fig. 1. Artist's view of the different components of the EURISOL facility. The Driver Linac supplies proton- and light ion beams with a power of up to 4 MW onto different isotope production targets. Radioactive isotopes extracted at low energies (30-60 keV) from the target/ion sources are mass separated in one or more sector magnets. They are either sent to a low-energy experimental area, or their charge state is increased in a "charge breeder" and they are accelerated in a post-accelerator. Several high-energy experimental areas are connected to the post-accelerator.

III THE DIVER LINAC

The linear accelerator supplies the drive beam for the RIB production target. A proton beam of 4 mA current and 1 GeV kinetic energy is the baseline for the EURISOL facility. In order to supply high intensity proton or light ion beams, linear accelerators are generally favored over synchrotrons because it is easier to keep beam losses under control. Beam loss in an accelerator has an immediate impact on the environmental releases of the facility by stray radiation and air/water activation, and on the lifetime of accelerator components, which is reduced by radiation damage. Beam losses are also responsible for the activation of all material in the accelerator area and therefore for dose equivalent rates in these areas. The possibility for access and for maintenance in accelerator shutdown periods depends on the level of dose equivalent rates. It is often assumed that an average loss rate of 1 W m^{-1} would assure the possibility for "hands-on maintenance" in the accelerator area. This statement needs to be analyzed in detail in the light of the obligation to optimize every intervention with exposure to ionizing radiation, and which cannot be satisfied with a global statement on average beam loss.

In EURISOL, it is planned that the driver linac supplies multiple production targets at the same time. One possible beam splitting scheme is to strip a fraction of the 4 mA H^- beam of one electron in a specially designed magnetic field. The neutral H beam, with a current of approximately 100 µA, would travel straight through a dipole magnet and through a stripper foil, emerging as a 100 kW proton beam for supplying one medium power production target. The remaining H^- beam would be bent by the dipole in the direction of the high-power target. Obviously, the beam splitter area will be the source of high beam losses in the stripper magnet, the dipole and the stripper foil. The recently commissioned SNS linear accelerator has been designed with a projected average beam loss power of less than 1 W m^{-1}, corresponding to 10^{-6} fractional loss at the highest energy.[2] However, at a carbon stripper foil, the fractional beam loss amounts to 3 10^{-5} (30 W lost beam power), causing an average dose equivalent rate of several mSv h^{-1} during accelerator maintenance, with local dose rate peaks of more than 100 mSv h^{-1} in the beam pipe. Other high-loss areas in the SNS accelerator are collimators, where localized peak residual dose rates also exceed 100 mSv h^{-1}. In these areas, local shielding and working procedures are obligatory measures in an optimized approach to radiation protection.

In future facilities, the losses must be quantified as precisely as possible in the design process in order to construct appropriate, reinforced shielding structures. Scaling of the fractional losses in the SNS stripping foil to EURISOL beam intensities results in a lost beam power of 120 W. In this situation, the activation of critical components may be so high, that the only possibility for maintenance is the exchange of components, possibly with remotely operated manipulators and tools.

IV THE ISOTOPE PRODUCTION TARGET

In present RIB facilities, so-called direct targets are predominantly used. In a direct target, the proton beam impinges on the target material and produces radionuclides by spallation and fission reactions. It is believed that direct targets can dissipate a beam power of up to 100 kW before reaching mechanical and thermal resistance limits. Therefore, the target assemblies conceived for the 4 MW proton beam are indirect fission targets, where nuclear fission of the target material is driven by neutrons from a spallation neutron source.

The schematic design of a fission target assembly consists of a liquid mercury spallation neutron source, similar to SNS but for 4 times higher beam power, surrounded by a target containing fissile material such as ^{232}Th, ^{235}U or ^{238}U. Figure 2 shows a schematic layout of the combined spallation source/ fission target.

The baseline design foresees uranium carbide (UC_2-C_x) as fissile material, made from either natural or depleted uranium. The target assembly contains approximately 18 kg of uranium.

The safety issues in such a target assembly are manifold. They are connected to

- the mercury spallation source, using a toxic, volatile liquid, which will be rapidly activated,
- the fissile material, containing large amounts of uranium or thorium,
- the prompt radiation from the target station.

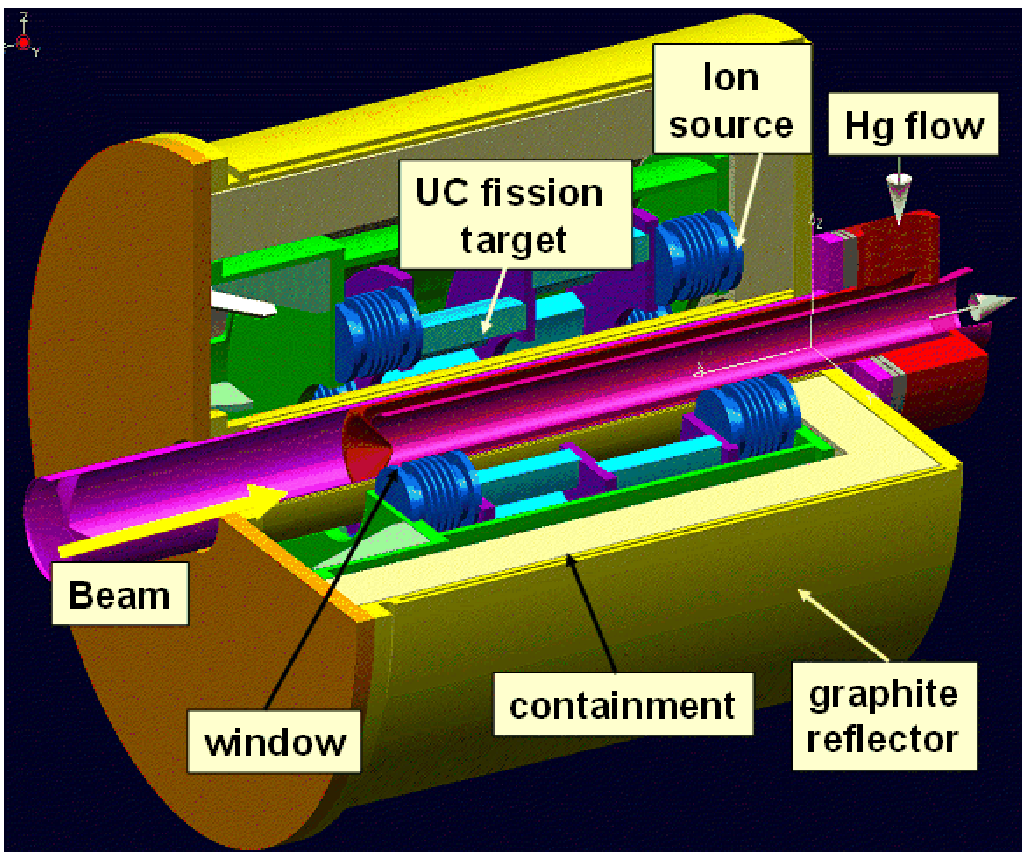

Fig. 2. Artist's view of the fission target, consisting of a liquid mercury spallation neutron source and a concentric arrangement of fissile material. The target has overall dimensions of 100 cm * 100 cm diameter. It contains approximately 18 kg of natural or depleted Uranium or Thorium.

IV A. The Spallation Source

First operational experience with a neutron spallation source using liquid mercury is gathered in the U.S. at the Spallation Neutron Source SNS, albeit at a 4 times lower bream power. The hazards from the toxic and volatile target material are augmented by the fact that it becomes highly radioactive after exposure to the proton beam. Dominant isotopes in the nuclide vector have half-lives exceeding several 100 years. After the first irradiation, the target material must be handled with all necessary precautions against accidental contamination. It has recently been observed at SNS, that spallation products from mercury adhere to surfaces of the mercury loop, causing unexpectedly high dose rates to maintenance personnel [3]. The spallation neutron source needs to be maintained in shielded hot-cells, taking account of the toxicity and radioactivity of the target material.

After the operational lifetime of the spallation source, it must be dealt with as long-lived radioactive waste. According to regulations in most European counties, a facility can only start operations if a plan for dismantling and waste elimination has been approved by the competent authorities. For large amounts of activated, liquid mercury no elimination pathway exists at present. Methods of solidification of mercury have been demonstrated with gram- amounts, but it is not obvious that they can be extended to the mass of several tons employed in a spallation source.

IV B The fission target

In a recent design of the target assembly [4], 18 kg of uranium are used as fissile material. The uranium carbide filled containers cover only a small part of the solid angle into which neutrons are scattered from the spallation source (Figure 2). This target arrangement is only half as efficient for isotope production as a standard ISOLDE target, where 0.35 fission products per proton on target are produced. Radiological optimization would call for a design where the additional proton beam power is efficiently transformed into isotope production. Nevertheless, the beam power of 4 MW as compared to 2.8 kW on a standard ISOLDE target will lead to isotope production yields which are approximately 3 orders of magnitude higher. It is assumed that the lifetime of a target assembly is 6 weeks. In this time it would receive 10^{23} protons from a 4 mA beam. Under these circumstances, the activity of the spent EURISOL fission target after 1 month of radioactive decay time would be in the range of $10^{13} – 10^{14}$ Bq of fission and spallation products, 10% of which are alpha emitters. The dose rate in 1 m distance of such a target would be in the order of several 10 Gy h^{-1}.

All handling of the spent target assembly will have to be performed in shielded, aerosol-tight hot-cells with manipulators. The waste from targets needs to be conditioned in a way that it does not present a hazard for the population even in the event of accidents with a small probability. In Switzerland for example, the operator of a facility must guarantee that accidents with a probability of more than 10^{-4} per year will not lead to a dose in excess of 1 mSv to a member of the public.

An additional hazard, unknown from today's direct uranium carbide targets, is the production of ^{239}Pu in a fission target. ^{239}Pu is the long-lived (half-life of 24500 years) intermediate product from neutron capture on ^{238}U, which decays within a few days into ^{239}Pu. The neutron capture cross section of ^{238}U is high enough in the neutron spectrum emerging from the spallation target (Figure 3), that more ^{239}Pu than all fission products taken together is produced. In a six-week production run, 16 g of ^{239}Pu would be produced in the target, in 3 or 4 annual runs, more than 50 g of plutonium would be produced in such a facility.

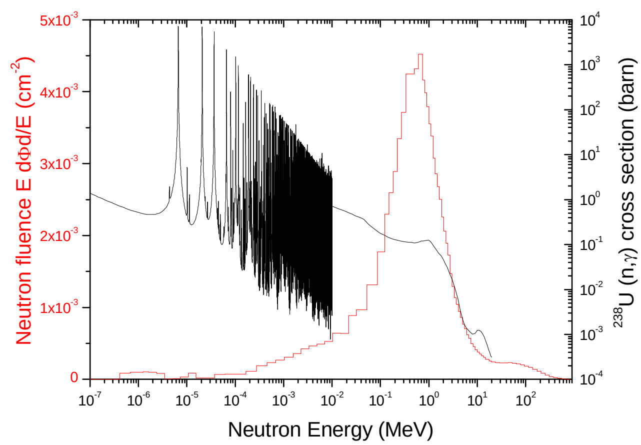

Fig. 3: Lethargy-plot of the neutron fluence spectrum emerging from a liquid mercury spallation target compared to the neutron capture cross section of ^{238}U, leading to the production of ^{239}Pu.

In some European countries the plutonium production together with the high activity content in the spent fission target assemblies would lead to a classification of EURISOL as "Nuclear Installation". Such an installation falls under the supervision of a nuclear regulatory body, usually concerned with nuclear power plants and fuel-cycle related facilities. Safety and safeguarding requirements (against dissemination of the fissile or fertile materials produced) are very stringent and it remains to be evaluated if they are compatible with the operation of a research facility which should grant easy, world-wide access to scientists.

Finally, as for the irradiated mercury, an elimination pathway must be defined for waste from the targets before their design can be approved. This will have to be done with respect to the legislation of the country which is going to host the EURISOL facility.

IV C Shielding of the target station

Shielding the secondary radiation of a 1 GeV, 4 mA proton beam which is entirely stopped in a massive target is, in principle, straightforward. Simple shielding formulae[5,6] have been validated at numerous occasions and they are shown to be applicable also in this case (Figure 4 [7]). It would be excessively expensive in computation time to estimate the attenuation of a massive bulk shielding with Monte-Carlo codes alone. Instead, attenuation coefficients are derived from fits to Monte-Carlo results with the FLUKA code [8] over a limited range. They allow an easy extrapolation of the shielding to very low ambient dose rates.

In order to attenuate the dose rate from the beam impact point to acceptable values of around one μSv h^{-1}, a bulk shielding of 2 m iron, followed by 8 – 10 meters of ordinary concrete is necessary.

Although the necessary shielding of a Multi-MW fission target can be determined by the extension of well-working concepts, it remains challenging for three reasons:

- the target assembly may need to be changed very frequently. As in SNS, one could imagine a target assembly mounted on a shielded "carriage" which can be moved out of the shielding massive into a hot-cell complex. In the case of a RIB target assembly, two hot-cells are required, one for handling the activated mercury loop, and a second one for handling the activated fissile target material with its highly alpha-toxic nuclide inventory.
- The purpose of a RIB target is to extract radionuclides from the target assembly. In this case, this has to be dose by penetrations through the meter-thick shielding. Similar issues arise in the design of neutron beam lines and shutters at SNS [9]. Very efficient means of beam transport must be implemented so that the gain in isotope production yields from a multi-MW target is not lost in the ion beam transport system, making the whole system obsolete.
- A large fraction of the material employed in the shielding will have to be deposited as activated and contaminated waste when the facility is dismantled. The high cost of this needs to be considered in the budget of the facility.

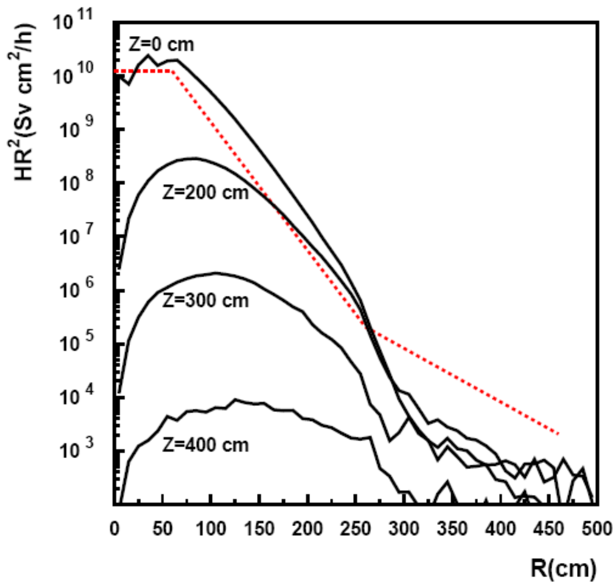

Fig.4 Comparison between the radial dependence of ambient dose rate H*(10)* in a composite shied made from steel between R = 50 cm – 250 cm, followed by ordinary concrete. The attenuation has been calculated by a Monte-Carlo code (continuous lines) and the shielding formula of Sullivan[3] (dotted line). The values have been multiplied with R^2 in order to eliminate the purely geometrical attenuation. The Monte-Carlo calculation has been performed for different distances from the beam impact point (Z=0) in direction of the beam. The simple shielding formula is conservative in the outer ranges of the shielding. The actual shield extends until radial coordinates of 8 to 10 meters, depending on the angle with respect to the beam direction.

V. EXPERIMENTAL AREAS

The aim of a radioactive ion beam facility is to deliver radionuclides to the detectors and other scientific experiments of the users. For this purpose, several experimental areas are foreseen in a future facility, for isotopes extracted at low energies from the target/ion source or for ion beams emerging at high energies from the post-accelerator.

With the possibility to extract radioactive ion beams from the Multi-MW target which are 3 orders of magnitude more intense than at present RIB facilities, the experimental areas will have little in common with what can be seen at ISOLDE or SPIRAL, for example. In these facilities, one tries to keep average ambient dose rates *H**(10) under the dose rate limit of a supervised radiation area in order to keep access and work organization in the areas as simple as possible. At ISOLDE, the ambient dose rates are kept below 3 μSv h^{-1} at permanently installed workplaces and below 15 μSv h^{-1} in passageways. At hot-spots, which are inaccessible to users, such as switchyards in the beam line system or beam stops in experiments, dose rates of 100 μSv h^{-1} have already been measured locally. In a future RIB facility with Multi-MW target the ambient dose rate will be 3 orders of magnitude higher. With an average ambient dose rate of 3 mSv h^{-1}, access would be severely limited, and experiments could not be operated.

The conclusion from this is, that "hands-on" nuclear physics experiments will be a thing of the past once EURISOL or a similar RIB facility takes up operation. Future experiments will have to be installed in shielded areas and must be operated from a distance. Access to the experiment will require optimization, assisted by radiation protection specialists.

Users will have to receive training so that they can assure their safety and the one of their collaborators during work on activated or contaminated experimental equipment.

VI. SUMMARY AND CONCLUSIONS

Radioactive ion beam facilities of the next generation are projected to be in operation from 2020 on. They will use a 1000-times more intense proton- or heavy ion beam to produce radioisotopes by spallation or fission. Consequently, the extracted radioactive ion beams are expected to be three orders of magnitude more intense than in present facilities.

In this paper, three areas were identified, where radiation protection at such facilities will meet new challenges. The unprecedented power of the proton beam will lead to increased activation levels in the driver linac area, in particular at the high-energy end, where the beam is distributed to different target stations. The target station by itself must be shielded by a 10- 12 meter thick shielding massive made from a combination of iron and concrete. Maintenance of the liquid mercury spallation target and the fissile material isotope production targets require processes which are entirely performed with manipulators in shielded and alpha-tight hot-cells. The production of ^{239}Pu in macroscopic quantities (50 g or more per year in an operation scheme which is presently discussed) will lead to an application of safety and safeguarding rules nowadays known only from nuclear facilities. Finally, the nuclear physics experiments of the future areas, will have little ion common with today's "hands-on" set-ups of detectors and computers, but they will have to be installed in shielded areas, where they have to function autonomously or by telecommand.

Radioactive waste, partially highly active and contaminating, will be produced in all areas of a future RIB facility and needs to be characterized. For liquid waste from the spallation neutron target, suitable solidification procedures need to be developed.

In the EURISOL Design Study which is financed by the European Commission in the 6th framework program, one work package deals with radiation protection. The strategy of the working group is to make various site-independent prospective studies of radiation protection aspects in different areas of EURISOL. Results on the shielding of the Driver Linac and the target stations, the activation of the target or of the soil around the facility were already obtained. Neither the limited resources available in a design study nor the insufficient level of detail with which the elements of the facility are designed so far allow for an engineering concept of the radiation protection features of EURISOL. This must be reserved for a future study, after the site of the future facility has been decided upon.

ACKNOWLEDGMENTS

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