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Radiological Protection Policy Aspects concerning the Design and Operation Modus of Medium Energy (< 1 GeV) or High Current ($>$ 25 MeV, ≈ 1 kA) Electron Accelerators Facilities

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Abstract

Radiation Protection in major research-facilities includes several aspects concerning their planning, the hazard-sources, the environmental protection and the general safety. The present paper includes a concise presentation of the approach to the radiation protection policies proposed for the Athens Race Track Microtron (250 MeV, 550 mA) and the Heraclion Modified Betatron Accelerator (25 MeV, 1 kA).

1 Introduction

Radiation Protection in major research-faciliuties includes several aspects concerning their planning, the hazard-sources, the environmental protection and the general safety.

The present paper includes a presentation of the methodological approach to the radiation protection policies prepared for several planning versions for the the Athens Race Track Microtron (RTM 250 MeV, 550 mA) and the Heraklion Modified Betatron Accelerator (MBA 25 MeV, 1 kA).

1.1 *Annual dose-equivalent limits*

According to the ICRP recommendation and the framework of radiation control legislsation in Greece, the annual dose - equivalent at the site boundary, must not exceed the 5 mSv/y. However, most of the research centers operating high-energy particle accelerators, have adopted lower reference levels, e.g. CERN: 1.5 mSv/y fence-post dose limit [CERN, 1981].

In the spirit of such reference levels, the design of the new facilities, as well as, the operation policy which will be adopted has as a goal, the limitation in exposure for those living outside the fenced area of the facility, below 0.5 mSv/y.

We should underline here, that the policy, which limit doses that might be received by persons, is distinct from the above mentioned fence-post dose limitation.

1.2 Skyshine

Radiation from an accelerator installation may extend out to large distances from the source. Radiation may reach individuals:

- Either directly, through a shield and in a straight line. This case is usually relevant for professionally exposed persons.

- Or indirectly, at large distances by way of air scatter. This case is relevant for the general public, living several hundred meters around an accelerator research facility.

This scattered radiation is termed "skyshine" and is usually due to relatively high levels of neutrons, escaping upwards through holes or thin parts of an accelerator shield in areas that are normally inaccessible during operation. These neutrons are then scattered in the air and a proportion arrive back down at ground level [13].

Practical measurements of neutron skyshine [6, 10] show that beyond 100 m from the source the skyshine dose rates varies as the inverse square of the distance from the source [13].

In the case of low energy and high power accelerators (as the Heraklion MBA facility) skyshine contribution to public exposure is negligible. In the case of accelerators with maximal energies over 200 Mev (as the Athens RTM facility), the expected dose rate, due to neutron skyshine at different distances from the facility, will be:

Distance	Dose equivalent rate
100 m	12 nSv/h
200 m	3 nSv/h
500 m	0.5 nSv/h

Assuming 2000 hours/year run-time for the Microtron, the expected exposure of the general public, living in the vicinity of the accelerator, would be between 0.024 mSv/y and 0.001 mSv/y. If we take into account that the mean dose-equivalent due to natural and civil exposure (e.g. medical) is more than 1 mSv/y, then the it becomes profound that the skyshine shall not be an important problem.

2. Site Planning

The Radiological Safety Aspects strongly influence the Site Planning. The major assumptions for the planning of the accelerator vault are following:

1. The accelerator vault must be buried, taking into account the natural features of the ground. Bulky items should be brought into the vault through a concrete, radiation protection door, moving on rails. Tracks are approaching through a ramp.

2. High-energy electron interactions with matter and estimation of the associated radiation parameters are necessary, in order to calculate the apropriate shielding of walls, roof and ceiling which determines the civil engineering parameters. Experimental halls may be formed through removable (equipment radiation protection) modular concrete 1 m thick and 2.5 - 3.0 m high walls, transported by a wall mounted 15 - 25 tn crane. At the end of the vault a beam dump area should be formed.

3. The connection to the Auxilliary Buildings, which will include Control, Engineering, Laboratories etc., must be done through a labyrinth. Cables and pipelines are guided through a maze, which will also enable personnel access and equipment transportation, on behalf of a lift and a staircase.

4. Probable future extensions are influenced, as far as location and orientation is concerned, by the shielding needs, since soil is usually the main shielding material. Appropriate orientation of the accelerator vault and of the future experimental rooms on the lot and location of the beam dumps is necessary, in order to take advantage of the ground morphology.

5. Determination in final architectural lay-out of the location, is influenced by the shape and the dimensions of mazes, shafts and penetrations so that safety and functionality are optimized.

6. Definition of accesibility policy, including an interlock system equipped with barriers, person-counters, panic buttons, warning devices and interlaced with area radiation monitors.

7. A network for stationary area (scattered, attenuated and activated components) radiation monitors, as NaI(Tl) detectors, must be included in the electrical engineering planning in the vault and the experimental areas, including alert (0.025 mSv/h) and alarm (0.050 mSv/h) set-points, interlaced with the interlock system and the control console. A network for stationary moderated BF_3-counters and Ionization Chambers for radiation field measurements around the facility should also be included.

8. Air and dust activation, as well as, the formation of noxious gases through radiolytic reactions, during the facility operation should be considered in the design of the ventilation system.

9. Water activation will affect the design of the cooling system and especially of the water-cooled beam dumps.

10. A spatious radiation physics calibration laboratory, equipped with gamma and neutron sources, as well as, a personnel and site dosimetry and environmental monitoring laboratory should be included in the room programme.

Associated with the Radiation Protection requirements, besides the above mentioned architectural considerations, special civil engineering problems result in, related to the structure and the support of the non - carrying shielding walls, doors, penetrations and other building elements.

Furthermore, electrical and mechanical engineering safety questions, concerning power supply, ventilation, cooling etc. will be also dealt with, under the viewpoint of radiological safety.

3 Main Aspects and Potential Hazards to be Encountered

Concerning radiological safety, following aspects, as well as, potential hazards have been mainly encountered:

- High-energy electron interactions with matter and estimation of the associated radiation parameters.

- Shielding calculations, interlocks and accesibility.

- Components, air, dust and cooling water activation.

- Radiolytic reactions and noxious gases formation.

- Hazards due to potential sources beyond ionizing radiations.

The starting points and the approaching technique is presented for the most important aspects:

4 Electromagnetic Cascade and Shielding Calculation

High - energy electron interactions with matter lead to effects and particles relevant to radiation protection purposes at the energy range up to 300 MeV [14] as following:

- Secondary photons (Bremsstrahlung).

- Photoneutrons, i.e. giant resonance (E $<$ 30 MeV).

- Quasi-deuteron effect (30 MeV $<$ E $<$ 140 MeV).

- Photopion channels opening E $>$ 140 MeV).

Shielding calculations can be based upon following realistic assumptions, based on the data of Alsmiller and Gabriel [1], [7]:

Assumptions ($E_{max} \sim$ 250 MeV, $I_{max} \sim$ 550 mA)

Lost Power:	2% continuously
H_{max}:	0.025 mSv/h
H_{fence}:	0.0025 mSv/h
d_{soil}:	1.70 g/cm^3 (n - TVL: 143 cm)
$d_{concrete}$:	2.35 g/cm^3 (n - TVL: 103 cm)

Rough calculation results in following barriers thicknesses and the corresponding constractions, for the energy range up to 300 MeV(e.g. Athens RTM). The corresponding shielding for low energy and high current accelerators are essentially lower.

Shielding ($E_{max} \sim$ 250 MeV, $I_{max} \sim$ 550 mA)

Struct. Element	Calculated Thickness	Proposed Construction
Ceiling Barrier	~3.5 TVL	2 m concrete + 4 m soil
Walls - soil	3.5-4.0 TVL	6-10 m
Door	~4.0 TVL	3 m concrete and unaccessible area
Dump (walls)	~5.5 TVL	12 m soil
Dump (ceiling)	~5.5 TVL	12 m soil
Dump (direct)	~8.5 TVL	20 m soil

Shielding (E_{max} ~ 25 MeV, I_{max} ~ 1kA)

Structural Element	Proposed Construction
Ceiling Barrier	0.2 m concrete + 1.5 m soil
Walls	5.0 m soil
Auxilliary Radiation Protection Wall	1.0 m concrete
Door	2 cm iron and 12 cm borax

Final calculations are carried out, after the final architectural design has been completed, taking into account the details and the final shapes of several elements.It is advisable to propose increased soil thickness, especially if the facility area allows for such an overestimation.

Designing the maze connecting the accelerator vault and the auxilliary buildings, concerning the transmission of thermal - neutron fluence rate, the curves of Maerker et al. have been taken into account [9].

It seems that the most efficient beam dump design is the MAMI B (Mainz RTM) one, consisting of an Al cylinder filled with Al spheres, fluted by cooling water and followed by a Cu block [4].

5 Radiaoactivation by the Electron Beam

Radioactivity may be induced in solid components of the accelerator, in air contained in the accelerator vault, experimental halls etc. and in water of the cooling systems [2, 5].

The most important radioactivity-inducing reactions are the (α, n) ones. The maximum possible saturation activity cannot exceed numerically (Bq) the photoneutron production rate (n/s).

Light elements (C - Al)	400 - 600 GBq/kW
Medium elements (Fe - Ag)	800 - 1700 GBq/kW
Heavy elements (Ba - Pb)	< 2000 GBq/kW

The saturation radioactivity produced by (α, 2n) reactions is about 5% of the above listed values for light elements and about 10% for heavy elements. In the same order of magnitude amounts the saturation radioactivity produced by all other procesess combined.

The activity, however, induced in reality, is considerably less, because many reactions do not lead to radioactive end products. Furthermore, products having half-lives less than 10 min or more than 10 years, might be ignored.

6 Component Activation

The components to be most suspected for activation are those that absorb most of the beam energy, in particular the beam dumps, the targets and if applicable, collimators.

For the nuclides relevant for the radiation protection, the corresponding saturation activities [11, 12], do not exceed:

Natural Aluminium:	22 GBq/kW
Natural Copper:	270 GBq/kW
Stainless Steel:	2000 GBq/kW

The expected dose-equivalent rates, at 1 m distance from a suspicious stainles steel component, should not exceed, 0.30 mSv/h, at time of accelerator turnoff.

Measurements carried-out by the author, at the NIKHEF AmPS facility (500 - 900 MeV), in Amsterdam, have shown, that the radioactivity actually induced in components, at several critical points, is much lower, than expected. The dose- equivalent rate measured at 1 m distance, have not exceeded 0.025 mSv/h.

Activation monitors will be installed near the door (sluice) and other critical points.

7 Air Activation

The interaction of bremsstrahlung with air nuclei causes mainly production of radioactive gases, in accelerators operating above the production threshold i.e. 10.55 MeV, due to giant resonance reactions. These interactions produce mainly O-15 and N-13 in air with 2.1 min and 10 min half-lives respectively [15].

The activity production rate in a layer of 1 m of air surrounding a target in which 1 kW of power from high energy electrons is dissipated is given by [13]:

$A = f \times Y \times P \times l^{-1}$

f: the fraction of electron energy that converts to gamma rays

Y: neutron yield in air (3 x 10^{-8} n/s)

P: path length of gamma rays in air (1 m —> 0.129 gr/cm2)

l: mean free path of gammas for air (56 g/cm^2).

For the Athens Microtron Facility, that means, that the mean radioactivity concentration obtained will be 0.0114 Mbq/m^3 and for the Heraklion MBA Facility 0.0007 Mbq/m^3, since the maximum permissible concentration (MPC) according to the ICRP Recommendation is 0.0740 MBq/m^3.

8 Activity Induced in Water

Radioactivity in water is mainly formed by the interaction of Bremsstrahlung, with the O-16 component of, water-cooled targets and beam dumps, as well as in ground water, outside the concrete shielding, around the Microtron building and especially around the beam dump. Average concentrations depend on [16]:

- the electron beam power

- the fraction of beam power directly absorbed in water, typically 10% for water-cooled metal dumps and operating cycle

- the exposed volume.

The maximal total saturation activity expected in the primary cooling system of the Athens RTM, taking into acount, that the maximum Electron Beam Power will not exceed 18.5 kW and taking into acount an energy absorbtion ratio of 10% in the dump, would be 675 GBq, including 611 GBq of O-15 ($T_{1/2}$ = 123 s), resulting in locally exposure rates of up to a few mSv/h which may easily be shielded. The corresponding maximal exposure rate after each MBA shot will not exceed 0.015 mSv/h in an 1 m distance from the beam dump or the target. The ground water level seems, in both cases, to be much deeper than the critical 11 - 13 m from the surface.

9 Production of Noxious Gases

Noxious gases produced by ionizing radiation are ozone O-3 and nitrogen oxides NOx. Ozone is the most toxic and may be produced in such quantities as to constitute a health hazard within the radiation room [17].

The saturation concentration Cs of ozone, in the case of no ventilation is [8] proportional to the effective decomposition time T_d and the ozone production rate p (l/min).

The expected mean ozone concentration (turnoff concentration, C_t) will be five times less than the threshold limit value (0.1 ppm) for the RTM and three orders of magnitude below the limit for the MBA.

10 Environmental Monitoring Program

Following measurement program should be set up, in order to ensure an effective environmental monitoring:

- On line photon and neutron site monitoring.

- Personnel and experimental site dosimetry (^{6}LiF/^{7}LiF albedo and polyethylene moderated dosemeters).

- Activation monitoring (locally survey meters, Ge - Multichannel Analyzer).

- Environmental monitoring and sampling system out of fence post.

- Background data aquisition.

A dedicated radiation protection and environmental monitoring laboratory should be provided.

11 General Safety Requirements

Mechanical Hazards in the facility are related with the planninig, installation and operation of overhead cranes, load elevators, machine tools, gas bottles, compressed air etc.

Further hazards are related with the design and the operation of the massive radiation protection doors and partitions or even with the installation of heavy items, as magnets.

Last but not least, cooling water or water processing unit pipelines as well malfunction or inadequate planning in rain-water drainage, could result in flood and an appropriate detection and pumping system should be installed.

Electrical hazards include the ones due to high voltage used in the klystron, the vacuum and beam-line monitoring instrumentation, short-circuit hazards concerning the high current magnet power-supplies, as well as, the ordinary electrical hazads met in an industrial environment.

Disturbances caused by the high frequency on the RTM signal cables and monitoring equipment (e.g. to ionization chambers, if not RF-shielded), should also be considered.

Closely related to electrical hazards, is the threat of fire and the related fire-protection system of the facility including individual smoke detectors combined with Halon extinguishers, upon each major functional unit or ceiling mounted.

Finally, a general accident limitation operational policy, including all the remaining miscellaneous hazards (chemicals, toxic materials as lead, LASERS, intra- laboratory traffic etc.) should be worked out, on behalf of the architectural and functional features of the facility.

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