RADIOLOGICAL PROTECTION FOR THE MILAN SUPERCONDUCTING CYCLOTRON

C. Birattari+, A. Fassò*, A. Ferrari+

+ LASA Laboratory, via F.lli Cervi 201, 20090 Segrate (MI), Italy.

* CERN, 1211 Geneva 23, Switzerland.

ABSTRACT

A superconducting cyclotron is under construction at the University of Milan: the maximum energy will range from 100 MeV/n for the lightest ions to 20 MeV/n for the heaviest ones. Only partial self-shielding is ensured by the iron: due to the complexity of the geometry of the machine Monte Carlo calculations have been performed in order to estimate neutron and gamma leakage through the machine yoke and the surrounding shielding, and to predict radioisotope concentrations in the cooling fluids and in the air. The reference source chosen for the calculations is a 200 MeV deuteron beam on a thick carbon target. A description of the security system is sketched and some consideration about contamination and activation problems are drawn.

INTRODUCTION

The Milan superconducting cyclotron is now under construction at the Accelerator and Applied Superconductivity Laboratories (LASA). After completion the accelerator will be moved to the Southern National Laboratories of Catania, to be coupled with a 15 MV Tandem. In Milan the cyclotron will be tested with various beams, axially injected from an ECR source; no experiment with the extracted beam is planned. The poles, the cylindrical magnetic yoke and the cryostat itself supply a thick iron self-shielding to the accelerator. However several penetrations have been machined radially and axially in the yoke and in the cryostat. Some of them are quite large and cannot be neglected in assessing radiation streaming from the machine. Only removable concrete block walls will be installed before the beginning of the beam tests (2000 hours planned), scheduled for the last months of 1990. The complexity of the geometry and the lack of data about neutron attenuation above 50 MeV, especially for iron, forced to perform Monte Carlo calculations. For this task the CERN version of the MORSE code[1] and the HILO-DLC87[2] multi-group cross section library were used.

Besides the assessment of shielding thicknesses, a few important problems are: the determination of activation of air, of cooling fluids, and of strongly irradiated components of the cyclotron; the installation of the security systems, and, finally, the installation of monitors for neutron and gamma radiation. Concerning this last point, the sensibility at high energy of commonly used detectors is under investigation[3].

NEUTRON SOURCE

The beam tests in Milan will be carried out with N^{4+} or lighter ions. Since only deuteron and α beams can be accelerated up to the maximum energy (100 MeV/n for fully stripped ions), a 200 MeV deuteron beam on a carbon target has been selected as a reference source for shielding calculations. A simple computer code has been written to calculate the spectrum and the angular distribution of neutrons emitted by 200 MeV deuterons incident on a thick carbon target: more details are given in ref.[4]. The calculated spectra are in good agreement with experimental measurements at several deuteron energies (ref. 4 and references therein).

GEOMETRY AND MATERIALS

The geometry of the problem is made up of two parts: the accelerator itself and the Cyclotron vault with the shielding walls and the surrounding areas.

Cyclotron

An extensive description of the assumptions made to simplify the complex geometry of the cyclotron can be found in a previous paper[4]. An horizontal cross section of the accelerator geometry is shown in fig. 1, where are also indicated the two points (A beam probe, B 1st deflector) selected as possible positions of the neutron source for shielding calculations; the point C (2nd deflector) was considered only in special runs for the assessment of dose rates from penetrations.

Concrete shielding and surrounding areas

The accelerator stands on three pillars inside a large pit (12x8 m^2 wide and 6.5 m deep). The concrete block walls will be installed around the pit: they will be 7 m high and their thickness will range from 2 m (for the lower 2.8 m) to 1 m.

In figure 2 a horizontal cut of the Hall, as schematized in combinatorial geometry, is presented. Doses at boundaries are representative of levels in the most critical occupied areas during machine operation.

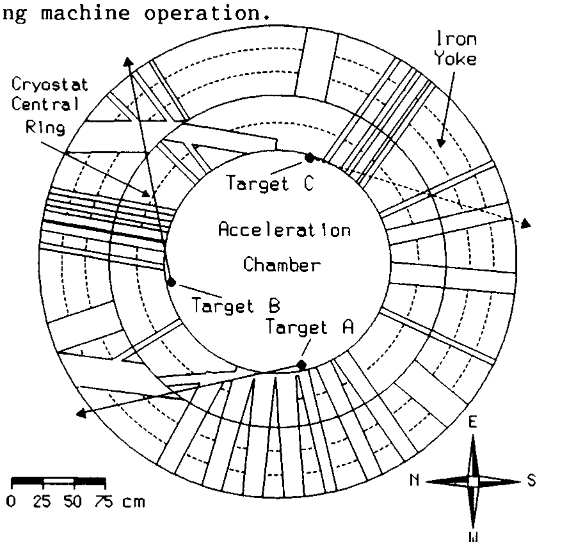


Figure 1. Horizontal cross section of the cyclotron geometry: dashed lines are fictitious boundaries introduced for weight setting.

CROSS SECTIONS

The HILO-DLC87[2] package is a coupled 66-neutron, 21-γ energy groups cross section library with P5 angular expansion, covering an energy range from thermal up to 400 MeV for neutrons, and from 10 keV to 15 MeV for γ. Some inaccuracies seem to be present in the HILO elastic cross section data for iron, at energies above 150 MeV[5]. However the need for cross sections for various elements up to a neutron energy of 200 MeV limited the choice to DLC87 and its improved version DLC119[6]. Unfortunately, DLC119 is restricted only to USA users.

MONTE CARLO CALCULATIONS

The details of the calculations, involving variance reduction techniques and flux scoring, have been extensively reported[4].

The differential energy spectra were folded with published[4] fluence-to-dose conversion factors to get the ambient dose equivalent H*(10) for neutrons and photons. Special runs were performed to compute neutron and photon spectra in points of special interest. Radiation fluxes inside specific accelerator components were scored to get suitable data to estimate cooling fluid activation; the same was done for the air around the accelerator. Special point detectors were used to evaluate radiation dose rates at the entrance of the largest penetrations in the concrete walls.

MONTE CARLO RESULTS

Dose rates inside and outside the shielding

The estimated ambient dose equivalent at various location for target A is presented in figure 2. Thermal neutrons and secondary γ rays have been considered only for case A. The calculations show that dose equivalent due to γ and thermal neutrons is a small fraction of the total (about 2 and 0.4%, respectively). The dose rates inside and outside the concrete shielding have been computed assuming a neutron yield, calculated with our model, of 0.705 neutrons per incident deuteron and a beam intensity of 10^{11} deuterons per second. Examples of neutron and γ spectra outside the shielding walls are shown in figures 3 and 4. Data for case B can be found in ref. 4.

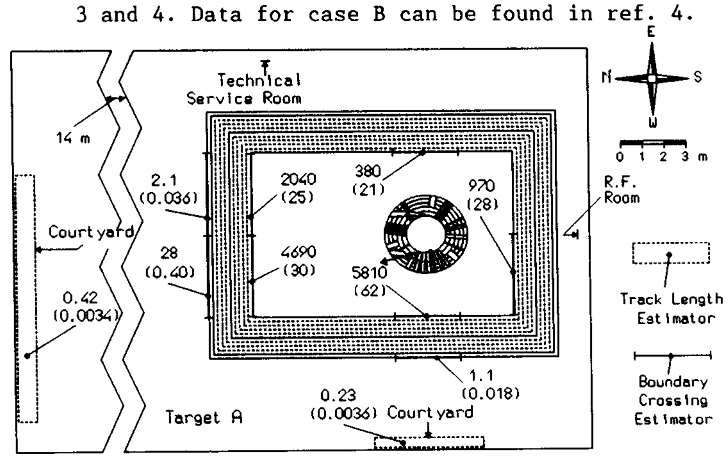
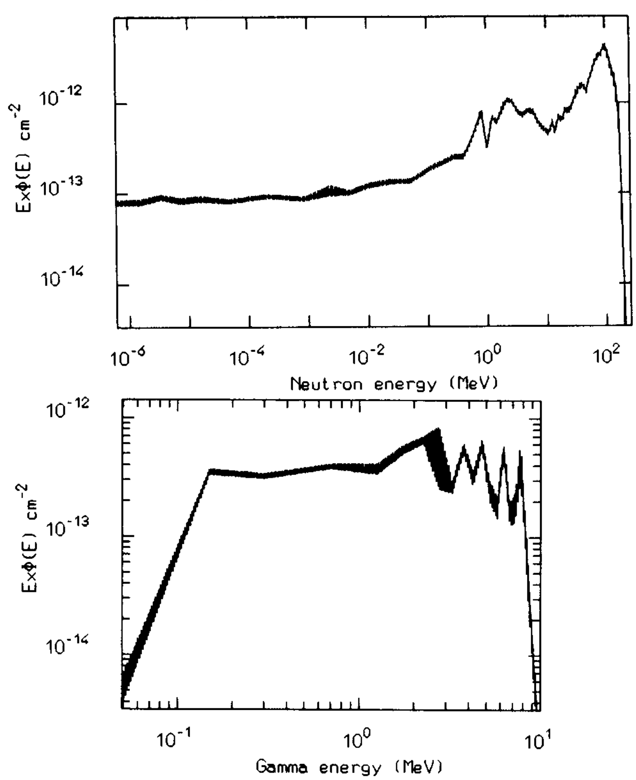


Figure 2. Horizontal plan of the Cyclotron Hall with the estimated ambient dose equivalent rate (μSv/h) due to neutrons and γ (between parentheses). Fractional standard deviations range between 2% and 20%.



Figures 3,4. Neutron and photon spectra scored by track length detector in the Technical Service Room (neutrons, target B) and on the Northern side of the Cyclotron Hall (γ, target A).

Dose rates at the exit of the penetrations in the concrete shielding

Neutron and gamma fluences at the entrance of the seven largest holes in the shielding were obtained from specialized Monte Carlo runs. Most of the penetrations are located far from the cyclotron median plane, and are reached only by few multi-scattered neutrons and photons, Since the CPU time needed for evaluate the radiation transmission directly from the Monte Carlo would have been extremely long, available universal transmission curves for multi-legged labyrinths were used to evaluate the attenuation factor for each penetration. Table 1 shows the main geometrical parameters, the attenuation, and the dose rate at the exit for the holes investigated, as obtained with the formulas of ref 7.

TABLE 1

Description of the penetration	Cross section & length cm²-cm	Att. factor (%)	Target	Dose rate at exit μSv/h
LHe pipe hole	1720 105	5.38	C	$4.1\cdot10^{1}$
LN pipe hole	400 100	.926	B	6.7
Cooling water pipe hole	5000 200	4.16	B	$9.3\cdot10^{1}$
Trim coil cables passage	4160 216	2.73	C	$1.7\cdot10^{1}$
Underfloor cable passage (South)	3750 200	2.92	C	$6.1\cdot10^{1}$
Entrance labyrinth@	42000# 1385*	$4\cdot10^{-3}$	A	$7.7\cdot10^{-1}$
He transfer line passage	1500 100	5.14	C	$3.5\cdot10^{1}$

@ Three-legged labyrinth
\# The second leg has a smaller section (3600 cm²)
* Total length of the three legs

Cooling fluid activation

The following nuclear reactions have been considered: $^{4}He(n,d)^{3}H$, $^{3}He(n,p)^{3}H$, $^{14}N(n,2n)^{13}N$, $^{16}O(n,spall.)^{7}Be$. The second reaction is esoenergetic and its cross section for thermal neutrons is very large (5327 barns at 2200 m/s) and furthermore should be corrected for the low temperature, so giving significant contribution to tritium production despite the very small isotopic abundance of ^{3}He. However since the abundance of ^{3}He in the cryostat helium should be much smaller than the natural one and the thermal neutron fluence inside the cryostat could be overestimated due to the room-temperature weighted cross section data, the figures presented in the following have to be regarded as conservative.

Neutron and γ fluences inside the cryostat and the polar expansion have been evalauted from a dedicated Monte Carlo run and then transformed into isotope activity by means of standard calculations. Cross sections were taken from the literature[8,9]. The rate of production of ^{3}H from ^{4}He (^{3}He) is estimated in $7.7\cdot10^{-2}$ ($1.2\cdot10^{-2}$) Bq/s, that leads to an activity of $5.5\cdot10^{5}$ ($8.6\cdot10^{4}$) Bq after 2000 hours; the estimated saturation activity due to ^{13}N is 0.1 MBq in the liquid, with a concentration in the cyclotron bunker air of 56 Bq/m³ assuming a rate of 0.5 h^{-1} for the air change; finally, the ^{7}Be saturation activity in water results to be 0.8 MBq.

Air activation

The following reactions have been considered in assessing the production of radionuclides in the air of the cyclotron bunker:
$^{16}O(n,spall.)^{7}Be$, $^{14}N(n,spall.)^{7}Be$, $^{14}N(n,2n)^{13}N$, $^{14}N(n,spall.)^{11}C$, $^{16}O(n,spall.)^{11}C$, $^{16}O(n,3n)^{14}O$, $^{16}O(n,spall.)^{13}N$, $^{16}O(n,2n)^{15}O$, $^{16}O(n,p)^{16}N$, $^{40}Ar(n,\alpha)^{37}S$, $^{40}Ar(n,p)^{39}Cl$, $^{40}Ar(n,\gamma)^{41}Ar$.

The isotope concentrations in the bunker air have been evaluated using the model of ref.9) and fluences from a dedicated run. The iron yoke of the cyclotron and the low intensity of the beam result in negligible concentrations for all the nuclides considered; no forced ventilation of the cyclotron bunker is therefore required. The activity at saturation are reported in table 2 with other data, for the isotopes whose concentration is at least 10^{-4} times the maximum permissible one; these figures have been computed assuming a rate of 0.5 h^{-1} for the air change.

TABLE 2

ISOTOPE	MPC MBq/m³	SAT.CONC. MBq/m³	ACT.REL.* MBq
^{11}C	7.0 10^{-2}	1.4 10^{-4}	1.2 10^{2}
^{13}N	7.0 10^{-2}	9.4 10^{-5}	8.1 10^{1}
^{14}O	2.0 10^{-2}	9.4 10^{-6}	8.1
^{15}O	6.0 10^{-2}	2.2 10^{-5}	1.9 10^{1}
^{16}N	2.0 10^{-2}	7.1 10^{-5}	6.1 10^{1}
^{41}Ar	4.0 10^{-2}	1.7 10^{-4}	1.5 10^{2}

* Activity release for 2000 hours.

SECURITY SYSTEM

The security system designed in order to rule the access to the bunker and to avoid any radiation hazard to the staff is composed by:

1) access control system
2) patrol system
3) interlock system
4) emergency system
5) Acoustic and optical alarm devices

All these systems are connected among themselves and with the computer control of the accelerator. The system combines a commercial device manufactured by Boselli-Schlage with dedicated components developed in our Laboratory and is based on radiofrequency operated proximity sensors and personalized badges. It is thus possible to allow or deny the admittance, to know the number and the identities of people present inside controlled areas at any time and to record the permanence time for each member of the staff.

The interlock system is extended to:

1) magnet
2) radiofrequency
3) electrostatic deflectors
4) ECR source
5) electric valve on the injection channel
6) electric valve on the extraction channel

The switching on of the various components is submitted to the effectuations of patrols and to the consense of the access control system. The emergency system switches off all those power supplies that can produce radiation hazards such as the ECR source and the RF system. The security system is integrated with optical (flashing lamps) and acoustical (sirens) devices that show the accelerator conditions and its working phase.

The operational conditions of the security system are: a) Unlock (free uncontrolled access), b) Lock (access restricted to authorized personnel), c) Close (no access). The first condition is active when all components are switched off. To switch on the various parts of the machine it is necessary to enter the "lock" condition, which can be activated only after a patrol in the bunker and in the building. The security system starts in this phase. The source can be switched on (and the beam accelerated) only in the "close" condition. This condition is activated when nobody is inside forbidden areas.

Radiation monitors

Neutron and gamma radiation will be detected by 4 pairs of monitors connected to a central controller and to local alarms, with two danger thresholds to be fixed between 10μSv/h and 250μSv/h.

The data presented in this paper show that the high energy part of neutron spectra is very important also outside shielding. Figure 5 shows an equivalent dose spectrum for the neutron spectrum of fig. 3: it can be clearly seen that neutrons with energies over 10 MeV contributes to about 67% of the total dose. The available rem-counters (Andersson Braun or similar rem counter) show a rapid decrease of counting efficiency above 10 MeV, which leads to a 55% underestimation of the dose equivalent[3] for the spectrum of fig 3). Moreover, the expected neutron spectra can vary considerably and in an unpredictable way by changing projectile, beam energy and target, thus making impossible the evaluation of a correction factor for the measured dose rate. It is thus necessary to develop a full-range rem counter. The design of such a counter is in progress[3]. The same considerations should apply to gamma radiation too, but, as already shown, gamma contributions to the dose equivalent are predicted to be less then 2%. Such a small value does not justify any particular effort to develop new counters; standard ionization chambers or G.M. counters will therefore be used.

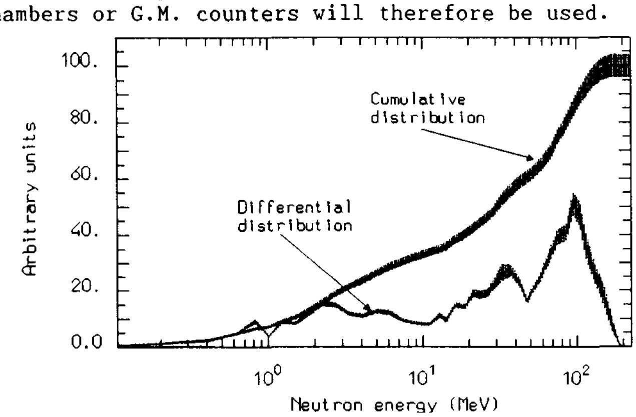


Figure 5. Differential (per unit lethargy) and integral dose equivalent contributions from the various energy groups for the spectrum of fig. 3.

CONCLUSIONS

The dose levels predicted outside the Cyclotron Hall show that shielding as designed should be adequate even under the conservative assumptions made about the source. A careful analysis shows that Monte Carlo techniques only, based on combinatorial geometry, seem to be capable to take into account the effect of the asymmetric distribution of ducts in iron. Cross section sets having the same degree of accuracy over the whole energy range would therefore be desirable. However, no such library seems to be generally available at present. Furthermore the hardness of the predicted spectra requires the development of new instrumentation for a reliable monitoring of the radiation levels.

The predicted activities in the cooling fluids are not worrying. Even though the overall activities should be released in the air for some accident (a quench), the concentrations would be less than the maximum permissible ones. Likewise air activation is low and a forced ventilation of the cyclotron bunker is not required.

A security system has been designed, which combines a commercial device for access control with interlocks, alarms and emergency devices on purpose developed.

REFERENCES

1. Fassò, A., The CERN version of MORSE and its application to strong-attenuation shielding problems, Proc. of the Topical Conf. on Theory and Practices in Radiation Protection and Shielding, Knoxville 22-24 April 1987, ANS, ISBN 0-89448-132-0, pp. 462-71.

2. Alsmiller,R.G.,Jr.,Barish,J., Neutron-Photon Multigroup Cross Sections for Neutron Energies ≤ 400 MeV, Nucl. Sci. & Eng., 1982, 80, pp. 448-80.

3. Birattari,C.,Ferrari,A.,Nuccetelli,C.,Pelliccioni,M.,Silari,M., An extended range rem counter, to be published.

4. Ferrari,A.,Fassò,A.,Birattari,C., Shielding calculations for the Milan Superconducting Cyclotron, 7th International Conference on Radiation Shielding, Bournemouth, 16-20 September 1988, Proceedings in press.

5. Zazula,J.M.,Cloth,P.,Filges,D.,Sterzenbach,G., Secondary particle yield and energy release data from intranuclear-cascade-evaporation model calculations of high-energy (20-1100 MeV) neutron interaction with elements of shielding and biological importance, Nucl. Instr. & Meth., 1986, B16, pp. 506-14.

6. Alsmiller,R.G.Jr.,Barnes,J.M.,Drischler,J.D., Neutron-Photon Multigroup Cross Sections for Neutron Energies ≤400 MeV (Revision 1), Oak Ridge National Laboratory, 1986, ORNL/TM-9801.

7. Stevenson,G.R., Neutron attenuation in labyrinths, ducts and penetrations at high-energy proton accelerators, Proc. of the Topical Conf. on Theory and Practices in Radiation Protection and Shielding, Knoxville 22-24 April 1987, ANS, ISBN 0-89448-132-0, pp. 408-417.

8. BNL 325, Neutron Cross section, 3rd ed.(1976).

9. Birattari,C.,Bonardi,M.,Ferrari,A.,Silari,M., Neutron activation of air by a biomedical cyclotron and an assessment of dose to neighbourhood populations, Rad. Prot. Dos. 14, 311-318 (1986).