Radiation Shielding Assessment of the Cyclotron Centre at INRNE-BAS

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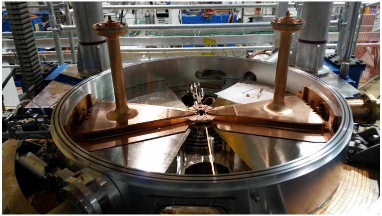


TR-24 cyclotron parameters:

- External CUSP ion source
- Accelerates H^- ions
- Extraction by stripping foils
- Beam energy: 15 – 24 MeV
- Beam current: 400 μA
- Upgradeable to 1000 μA
- Turbomolecular and cryo vacuum pumps (vacuum:5×10^{-7} – 10^{-6} Torr)

- PET: ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{124}I, ^{64}Cu, ^{68}Ge
- SPECT: ^{123}I, ^{111}In, ^{67}Ga, ^{57}Co, ^{99m}Tc

50 weeks/year x 5 days/week x 2 hours x 2 sessions/day = 1000 hours/year
20000 hours/20 years

- H*(10) during target irradiation for production of 18F;
- Evaluation of the residual dose rate after an irradiation session of a target for ^{18}F production;
- Activation of the bunker walls after the 20-year period of cyclotron operation.

Monte Carlo Method

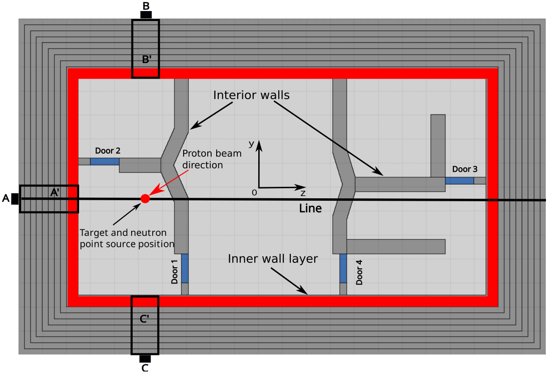
- The Monte Carlo method is a computational tool for modelling and analysing stochastic processes through repeated random sampling.
- In physics - transport and interaction of particles with matter.

FLUKA code [1]

FLUKA is a fully integrated particle physics Monte Carlo simulation package. It has many applications in high energy experimental physics and engineering, shielding, detector and telescope design, cosmic ray studies, dosimetry, medical physics and radio-biology.

- 60 particles and heavy ions;
- e^-, muons - 1keV to 1000 TeV;
- photons - 100 eV to 10000 TeV;
- hadrons - 100 keV to 20 TeV;

Geometrical model of the bunker and studied configurations



Implemented geometrical model of the bunker (look from above)

- Geometrical model of the bunker: outer walls - thickness 2.5 m; inner walls - thickness 60 cm; inner dimensions - 17 m (length) $\times$ 9 m (width) $\times$ 3.25 m (height).
- The red arrow shows the beam direction and points at the target position.
- Two bunker configurations are considered
  - configuration 1 - standard concrete with Portland cement (CPC)
  - configuration 2 - low activation concrete (LAC 50)

Materials set in the models

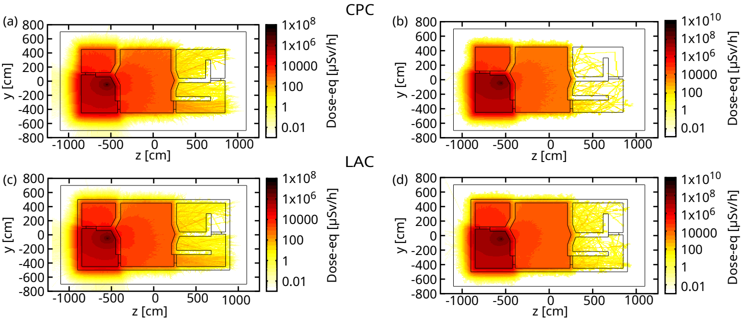
CPC ($\rho = 2.3$ g/cm^3), LAC ($\rho = 2.2$ g/cm^3), BP ($\rho = 1$ g/cm^3) and paraffin ($\rho = 0.93$ g/cm^3) are the materials set in our FLUKA models. The values of the trace elements in the concrete are marked with * are taken from literature and are measured in ppm.

Elements	Mass Fraction % CPC [2,3]	Mass Fraction % LAC[4]	Mass Fraction % BP[3]
H	1	0.721	12.5
C	0.1	8.915	77.5
B	-	-	10
O	52.9	47.772	
Na	1.6	0.076	
Mg	0.2	0.24	
Al	3.4	0.275	
Si	33.7	1.241	
K	1.3	0.033	
Ca	4.4	40.514	
Fe	1.4	0.063	
S	-	0.088	
Cu	-	0.008	
Sr	-	0.034	
Eu*	0.88	0.023	
Co*	12.9	0.75	
Ta*	0.5	-	
Cs*	1.25	0.052	
Sc*	11.5	-	

Results and Discussion - Part I

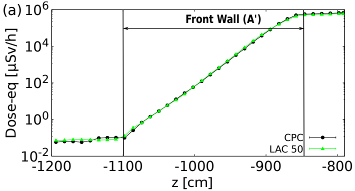
Part I: H*(10) during target irradiation for production of ^{18}F

- In the first part of the study we obtained results for the two configurations of the bunker for direct irradiation of the target - 24 MeV, 100μA



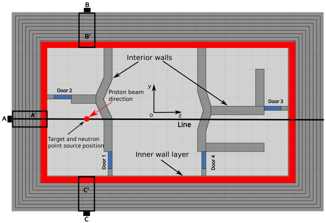
*Distribution of the gamma (a, c) and the neutron (b, d) ambient dose rate H(*10), for the two configurations (CPC, LAC 50).*

- This is the distribution of the radiation fields of the secondary particles, photons and neutrons, generated during the target irradiation.
- There is no is no significant difference in the distribution of the radiation fields.



Attenuation profiles of the gamma (a) and neutron (b) ambient dose equivalent rates in the front wall of the bunker and outside it, expected at 100 μA.

- The density values of the two concrete types are close -> CPC ($\rho = 2.3$ g/cm^3), LAC ($\rho = 2.2$ g/cm^3)
- The attenuation profiles of the gamma ambient dose radiation almost overlap.
- The fluctuations of the attenuation profiles of the neutron radiation fields, are stronger as the wall depth increases. This is expected since very few neutrons reach this part of the wall and the error of the calculations increases to more than 40%.

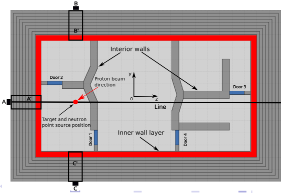


Part I: H*(10) during target irradiation for production of ^{18}F

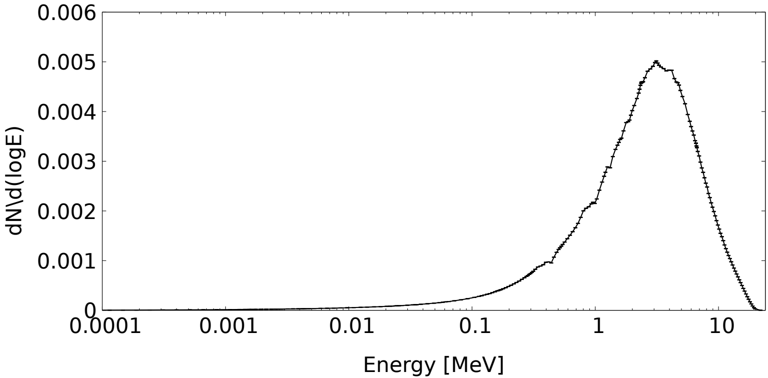
Gamma and neutron ambient dose equivalent rates outside the bunker.

Wall	Gamma maximum dose rate [μSv/h]	Neutron maximum dose rate [μSv/h]	Working load gamma average dose rate [mSv/y]	Working load neutron average dose rate [mSv/y]
	CPC			
Front	$0.10 \pm 8\times10^{-3}$	$0.003 \pm 1\times10^{-3}$	0.10	0.003
Right	< 0.001	< 0.001	< 0.001	< 0.001
Left	$0.06 \pm 8\times10^{-3}$	< 0.001	0.06	< 0.001
	LAC			
Front	$0.08 \pm 5\times10^{-3}$	< 0.001	0.08	< 0.001
Right	$0.003 \pm 9\times10^{-4}$	< 0.001	0.04	< 0.001
Left	$0.04 \pm 4\times10^{-3}$	< 0.001	0.003	< 0.001

- annual dose load -> a conservative estimate based on the constant presence of personnel in areas outside the bunker during accelerator operation
- The maximum value of the gamma ambient dose equivalent is about 0.10 μSv/h
- Both configurations provide effective shielding from the secondary gamma and neutron radiation fields.



Results and Discussion - Part II



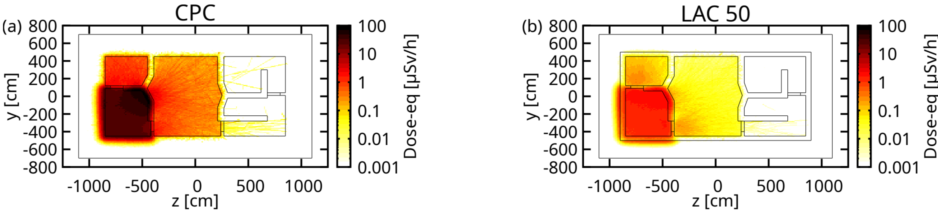
Neutron energy spectrum per primary proton generated by the $^{18}O(p,n)^{18}F$ reaction obtained from our present FLUKA simulations.

- $(1.16 +/- 0.0104)\times10^{-2}$ [neutrons/primary proton];
- Wall activation - secondary neutrons;
- For the same number of primary particles lower standard deviation with the neutron source.

Main radioisotopes found with the most probable production reactions: ((n, γ)[5] and (n, p)), their half-life, clearance level and cross section.

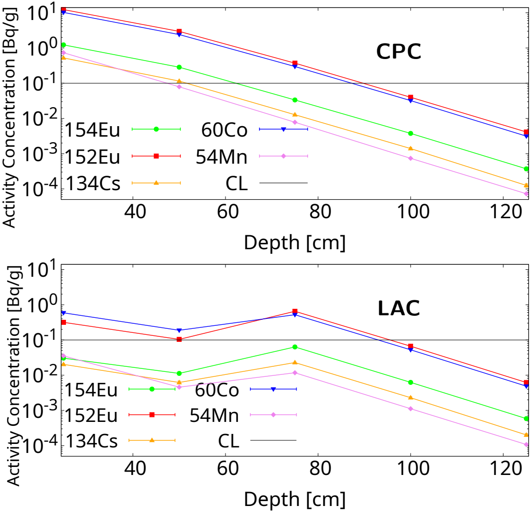
Nuclide	$T_{1/2}$	Clearance level [Bq/g]	Reaction	Cross section [barn]
^{154}Eu	8.6a	0.1	^{153}Eu(n, γ)^{154}Eu	312
^{152}Eu	13.5a	0.1	^{151}Eu(n, γ)^{152}Eu	9200
^{134}Cs	2.06a	0.1	^{133}Cs(n, γ)^{134}Cs	30.3
^{60}Co	5.27a	0.1	^{59}Co(n, γ)^{60}Co	37.18
^{46}Sc	83.8d	0.1	^{45}Sc(n, γ)^{46}Sc	27.2
^{54}Mn	312.3 d	0.1	^{55}Fe(n,p)^{54}Mn	0.59

Part II: Activation of the bunker walls after the 20-year period of cyclotron operation



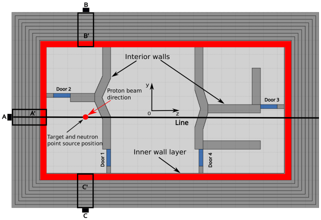
- Distribution of the ambient dose equivalent rate inside the bunker for the (a) CPC and the (b) LAC 50 setups, 1 month after 20 years exploitation.
- In the case of LAC 50 the dose rates inside the irradiation area are significantly lower in comparison to the CPC setup - 80 μSv/h (CPC setup) and 3 - 4 μSv/h (LAC 50).

Part II: Activation of the bunker walls after the 20-year period of cyclotron operation

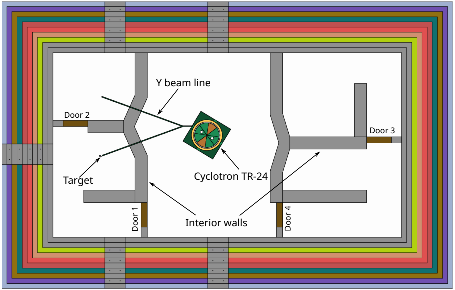


In-depth activation profile in Location 1.

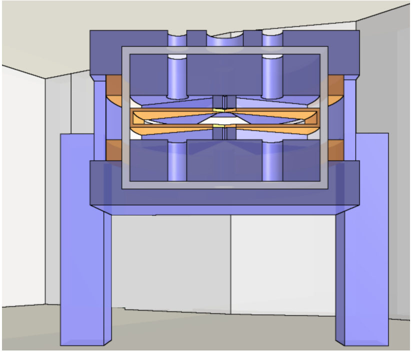
- The specific activity increase for LAC 50 is at the point where the CPC walls start.
- For LAC 50, after 27y , the activity of all radioisotopes will be below the clearance level whereas for CPC - 94.5y.



Updated Cyclotron Model & Preliminary Results



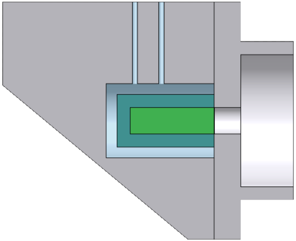
Implemented geometrical model of the bunker with the cyclotron (look from above)



Cyclotron model with it's main components

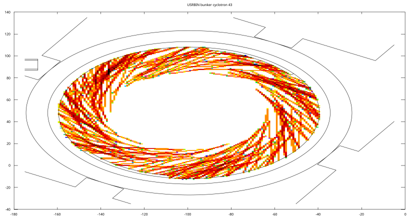
- Beamline, reinfororcing steel rods in the walls;
- Cyclotron body, vacuum chamber, coils, magnets, dees.

Updated Cyclotron model II



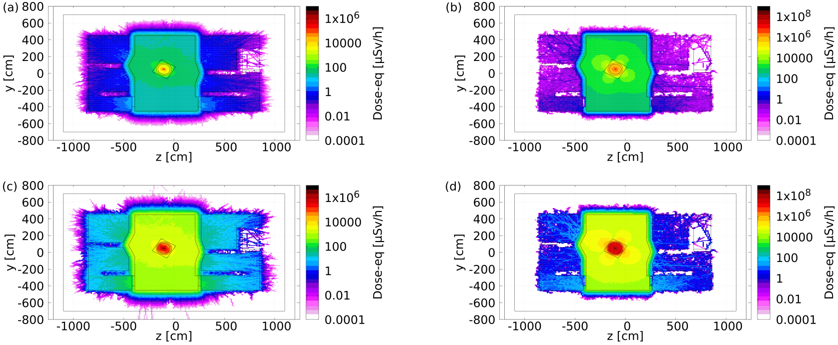
Implemented model of target for ^{18}F production

- Materials: body- Al, capsule - Nb; foil - Havar;
- Size: l = 110 mm , d = 90 mm;
- Capsule volume 2.5 ml; target is designed for maximum beam current 100 μA;



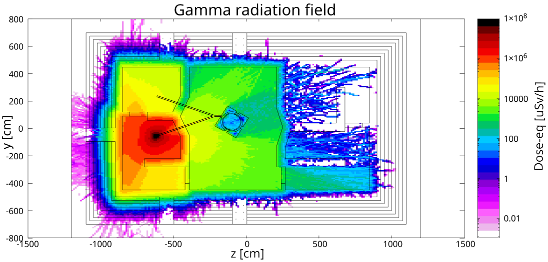
Modelled source of localized tangential beam losses in the cyclotron vacuum chamber due to interactions with air molecules.

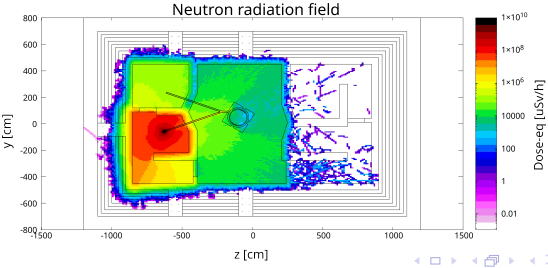
Preliminary results: Distribution of radiation fields from beam losses in the cyclotron vacuum chamber



Ambient dose-equivalent, $H^*(10)$, distributions for (a,c) gamma and (b,d) neutron radiation during cyclotron operation with beam losses of (a,b) 0.1% and (c,d) 3%

Preliminary results: Distribution of gamma and neutron radiation fields $H^*(10)$ during irradiation





Conclusion

- This research is aimed at the preliminary assessment of the radiation shielding of the Bulgarian National Cyclotron Centre at INRNE-BAS.
- The distribution of the radiation fields in and around the bunker was obtained during target irradiation for production of ^{18}F. It is shown that for the two considered configurations the radiation fields are effectively shielded.
- Distribution of long-lived radioisotopes in bunker walls. Replacing the CPC in some parts of the bunker walls with LAC leads to a significantly lower specific activity of the long-lived radioisotopes and, respectively, time required for their decay below the clearance level is shorter.
- Updated model of the bunker with implemented cyclotron and beam line. Preliminary results for the distribution of the radiation fields during cyclotron operation are presented.

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Radiation protection studies for the INRNE-BAS cyclotron facility using Monte Carlo FLUKA code

A. Demerdjiev, D.T. Dimitrov [1], D. Tonev, N. Goutev, G.D. Dimitrova, E. Geleva, S.G. Genchev

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