Activation Study of a PET Cyclotron Bunker for the decommissioning plan with Monte Carlo code Fluka

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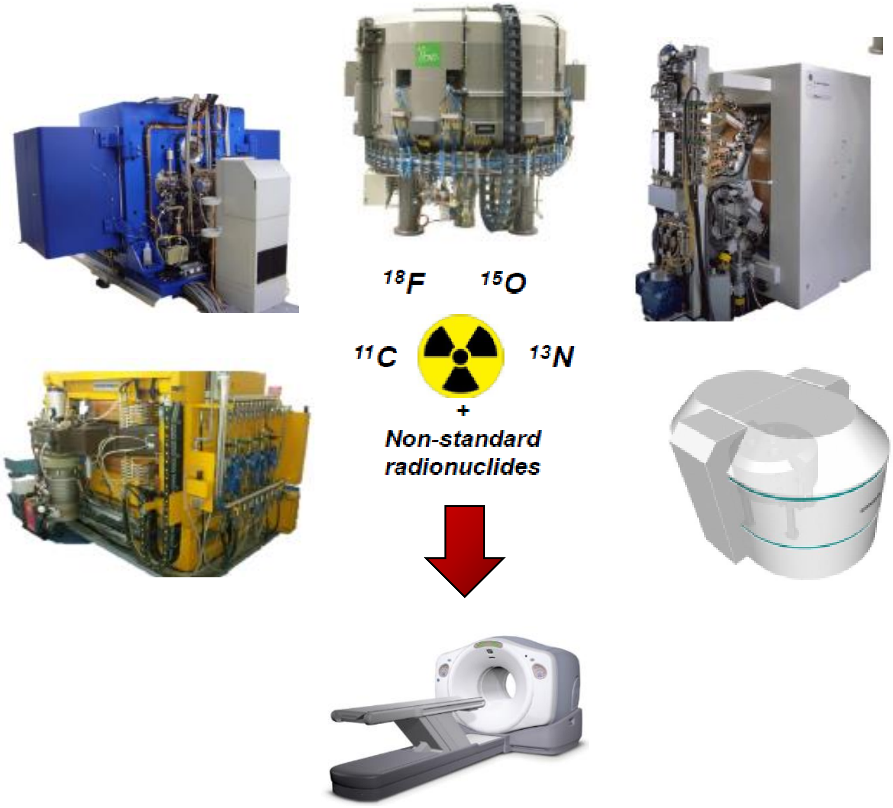
Introduction

- The use of accelerators in the medical field has grown significantly in the last two decades.

- The estimated life expectancy, as well as the reasons for shutting down accelerators can be different:

  - financial or political issues;
  - market evolution;
  - technological improvements:
  - changes in institution goals;
  - aging of equipment;
  - ….



According to IAEA in the world there are actually 15000 accelerators installed, of which only a few hundred for research while 97% are used for medical and industrial application

Introduction

In Italy there are 36 PET cyclotrons.
Most of these have been operational for 10-15 years.

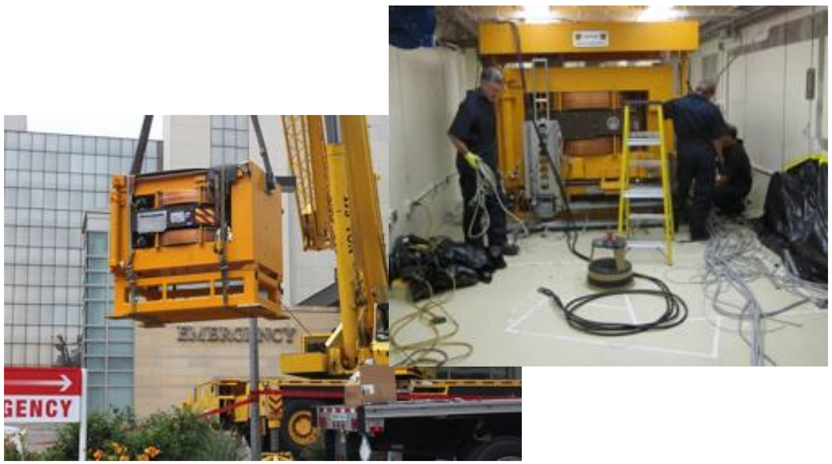
During the operational life some subsystems of the cyclotron itself and the concrete walls of the bunker become slightly radioactive due to the activation of metals and rare earth's present.

When considering the dismantling of such accelerators, considerable amounts of low level solid radioactive waste (several thousand of m^3 of concrete, plus several hundred kg of metal) have to be taken into account.

Introduction

State of the art

- PET Cyclotron decommissioning have been sporadically described in the technical literature
- There are no specific international standards and guideline documents



Aim of this work is to define a Monte Carlo approach for the assessment of activation levels of a PET cyclotron bunker

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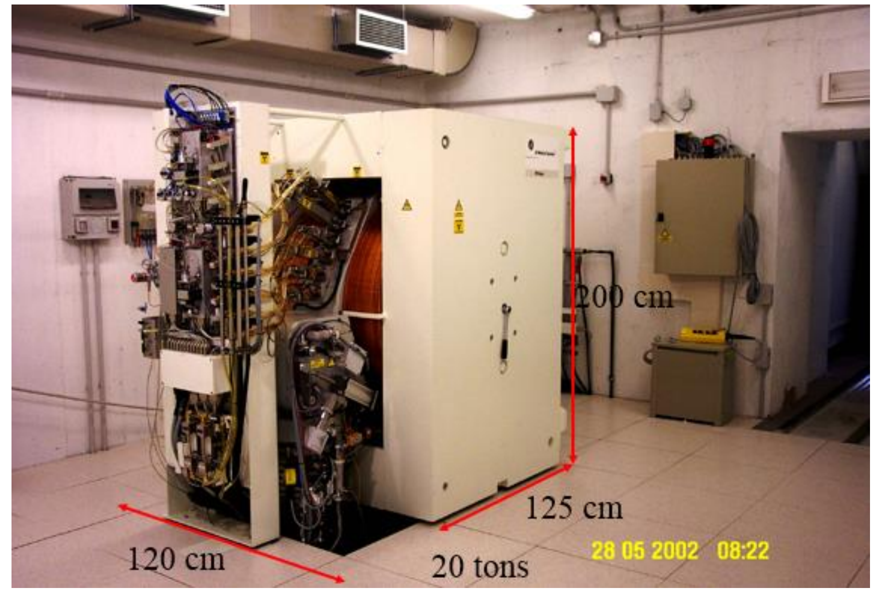
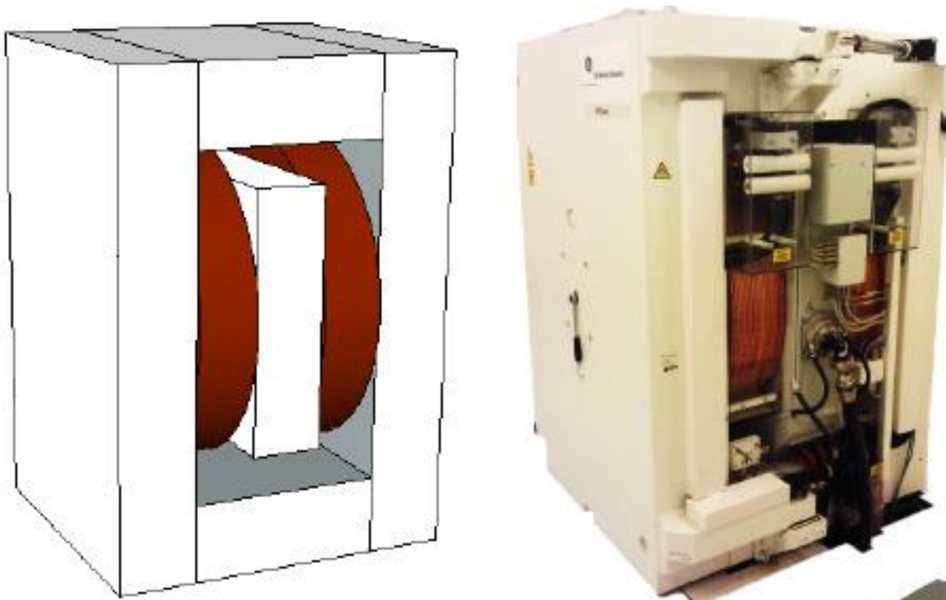


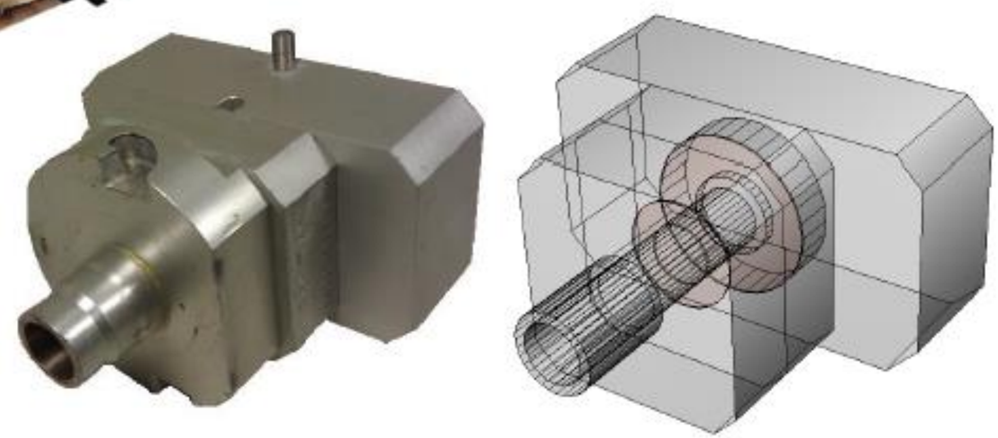
The GE PETtrace cyclotron (16.5 MeV) installed at “S. Orsola-Malpighi” University Hospital (Bologna, IT).

Typical daily production irradiation is made for 60 min with beams currents of 60 µA.

The Model: GE PETtrace cyclotron

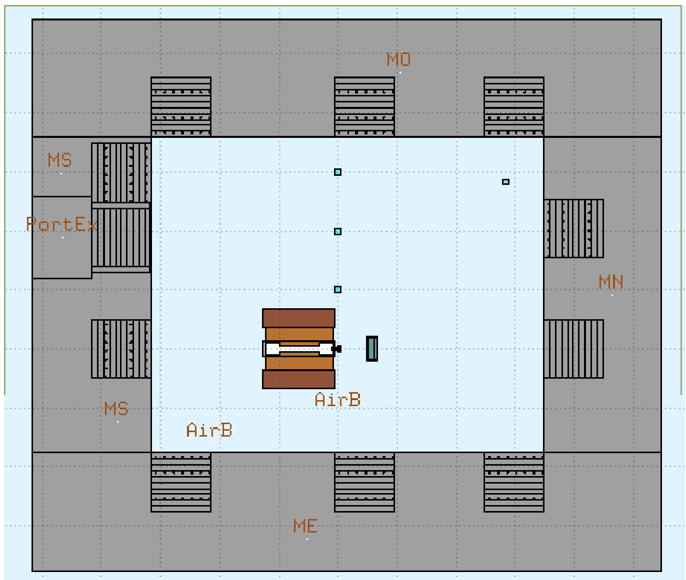


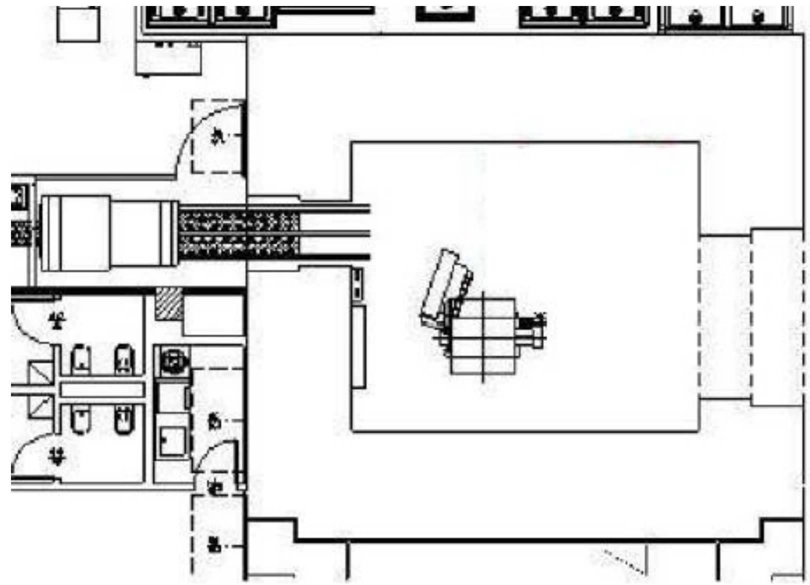
3D Monte Carlo model of the
PETtrace cyclotron
(GE Healthcare, Uppsala, Sweden)



3D Monte Carlo model of the $^{18}F^{-}$ target
(GE Healthcare, Uppsala, Sweden)

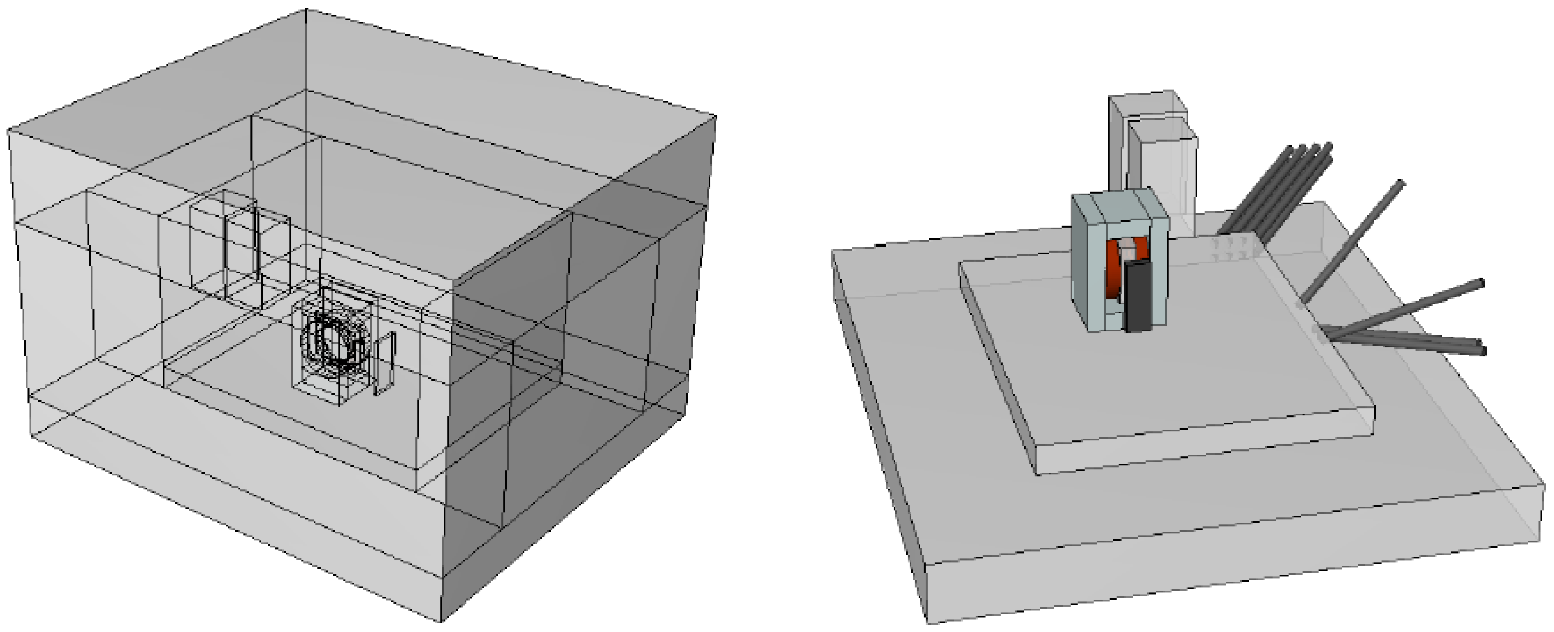
The Model: Bunker





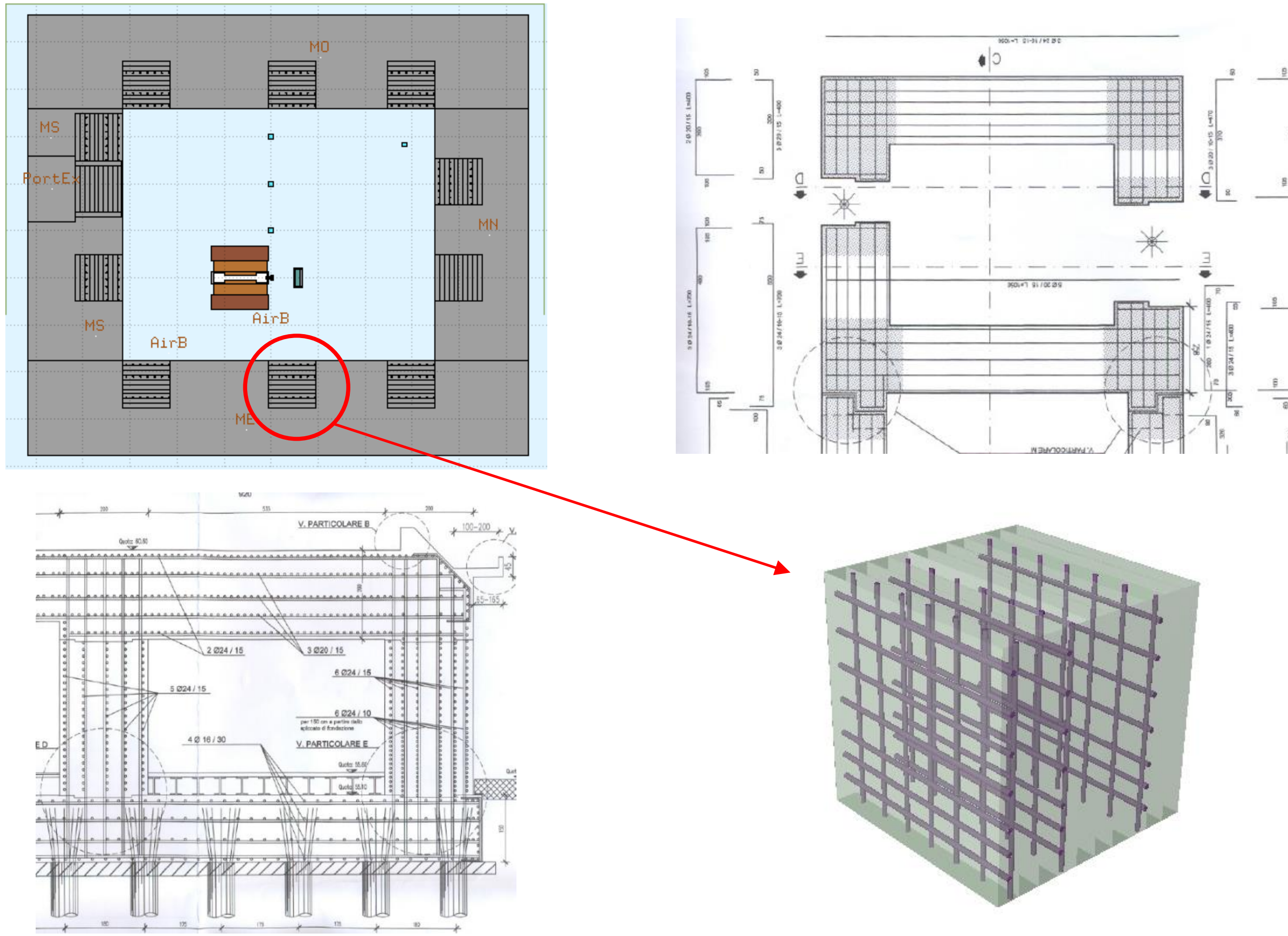
Section of the FLUKA Monte Carlo model and comparison with the original technical drawing of the bunker.

The Model: Bunker



3D Monte Carlo model of the S. Orsola-Malpighi cyclotron vault.
Detail of the pipes that contain the delivery lines, the RF cables, the control cables, etc.

The Model: Bunker



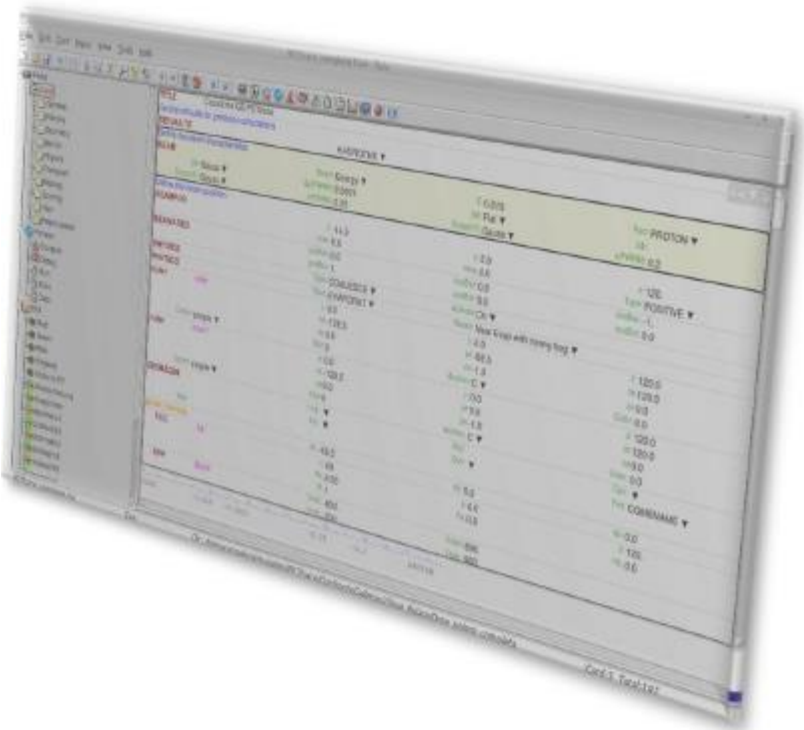
. Detail of the reinforcement rods

Input parameters

- **DEFAULTS:** NEW-DEFA
  - Transport of electrons, positrons and photons enabled
  - Low energy neutron (<20 MeV) transport on down to thermal energies included;
  - Delta ray production enabled
  - Heavy particle bremsstrahlung activated with explicit photon production above 1 MeV
  - Heavy particle e+/e- pair production activated with full explicit production

- **PHYSICS & TRANSPORT**
  - Coalescence and Evaporation enabled
  - NO Biasing

- **SCORING**
  - Neutrons fluence (USRBIN)
  - Activation (RESNUCLEi)
  - Protons/Neutrons spectra (USRBDX)

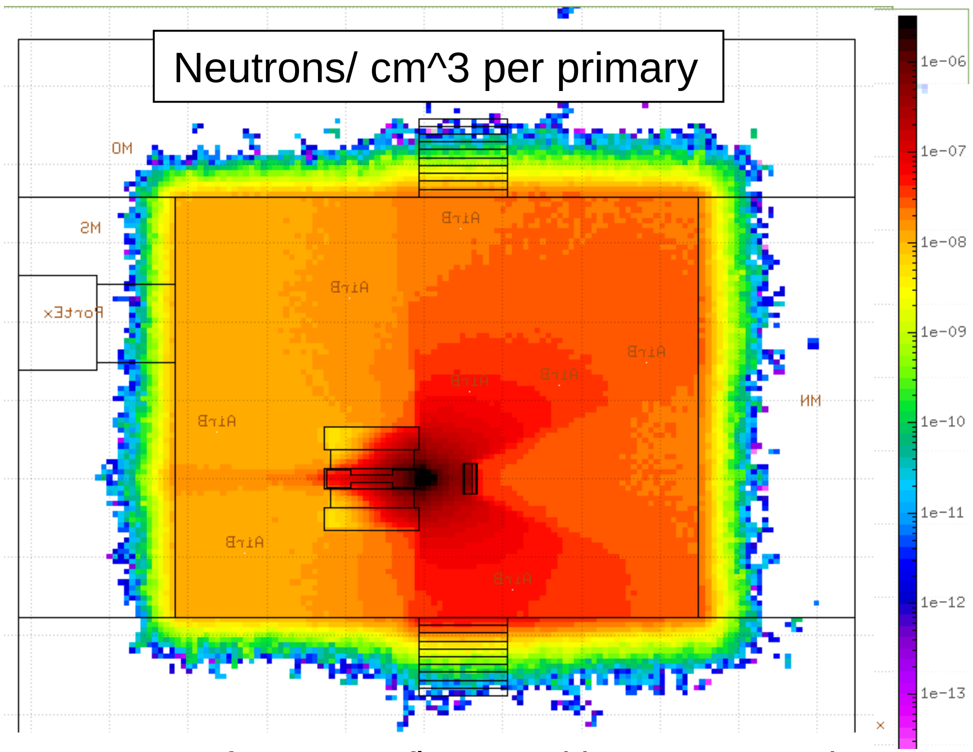


Source: 16.5 MeV Proton pencil beam

Primary particles:
5×10^{11} protons simulated

~ 4×10^{-3} neutrons/ primary proton

2×10^{9} neutrons



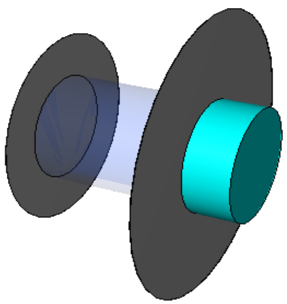
Score of Neutrons fluence with USRBIN card simulating 1×10^{9} protons as primary particles

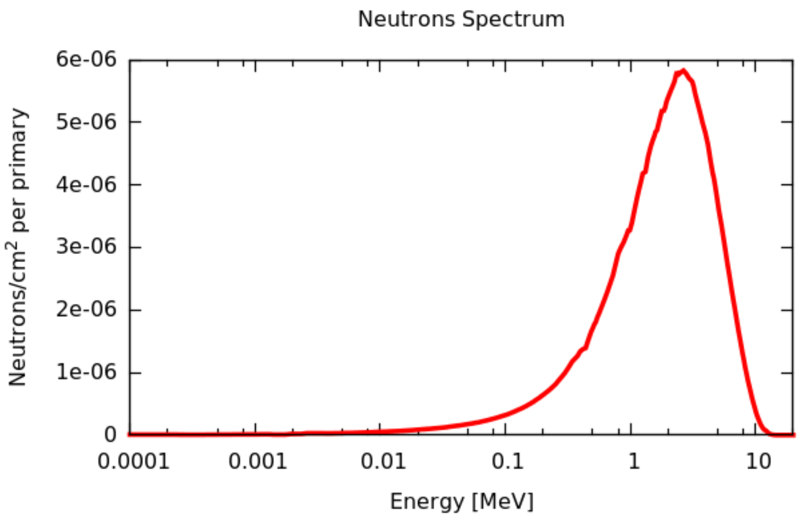
- Processor: i7-4790
- N° core: 4 (8 thread)
- N° runs: 8
- N° cicle: 5

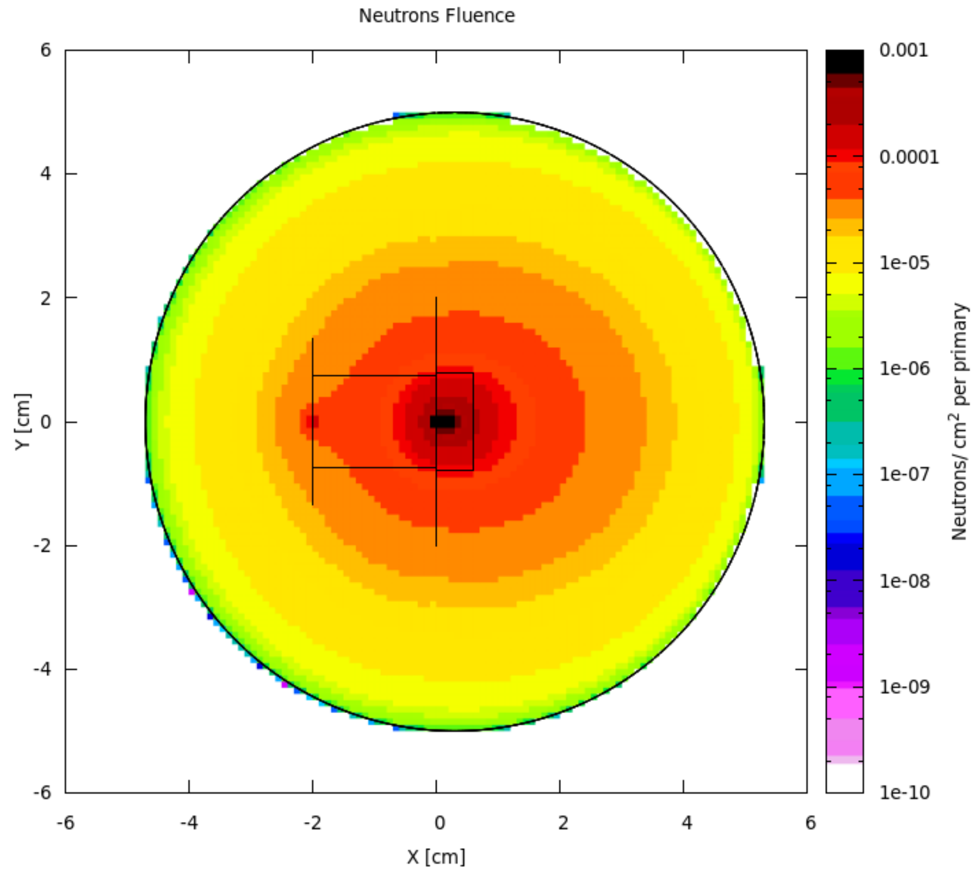
Simulation Time: 50 days

Secondary Neutrons spectrum assessing

- 16.5 MeV Proton beam
- Score of secondary neutrons crossing target region with USRBDX card







Neutrons source: Source.f

- Neutrons source was modelled as an isotropic point source located inside the target with the energy spectrum obtained.

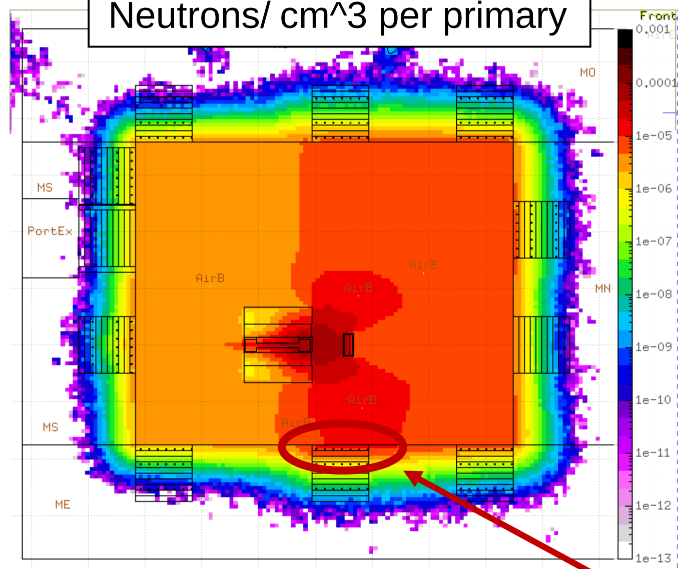
OPEN	Unit: 99 ASC ▾		Status: OLD ▾		
	File: spettroneutroni.txt ▾				
SOURCE	#1: 99.	#2:		#3:	
sdum:	#4:	#5:		#6:	

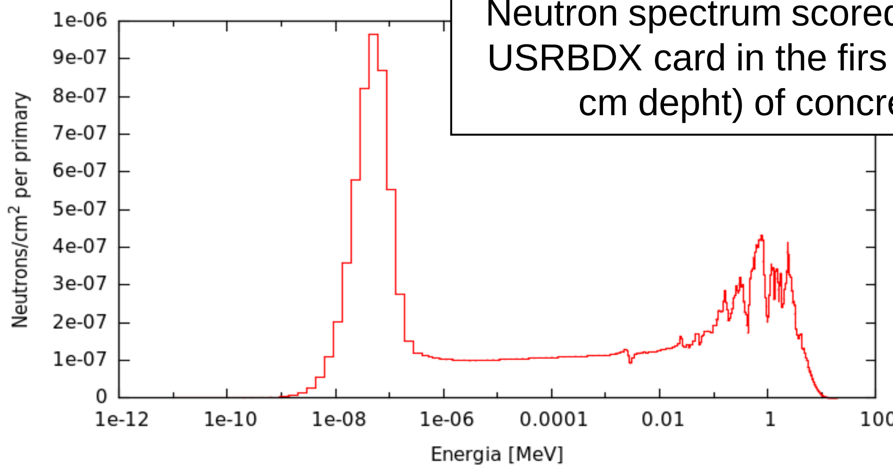
```
*  |  *** User initialization ***
*** Read the logical unit where to put temporany the source spectrum file
*** from SOURCE card WHAT(1).
*** Note: The histogram is read only at the fisrt call of the routine.
*** Filename is given through the OPEN card (same logical unit in ACS, status
*** OLD, filename)

         LUNRD = NINT(WHASOU(1))

*** Read the histogram as Emin, EMax, FLUence, ERrror%.
*** WARNING: The first value (of Energy and Fluence) should have be 0
*** in order to define the lower energy limit

         N = 0 !Counter set to 0 at the beginning

         SUM = ZERZER    ! Build cumulative sum
         Emin = ZERZER
         EMAX = ZERZER
 10      CONTINUE
             READ (LUNRD, '(A)', ERR=9999, END=20 ) LINE
             READ (LINE, *, ERR=10) Emin, EMAX, FLU, Er

             N = N + 1
             IF (N .GT. NMAX) !Check to not be over NMAX
     &            CALL FLABRT('SOURCE','Please increase NMAX')
             IF (N .EQ. 1 .AND. ABS(FLU).GT.AZRZRZ) !Check first value=0
     &            CALL FLABRT(
     &                 'SOURCE','ZERO was was expected as first value')

*** Create cummulative sum of events! dN=dE*V
             SUM = SUM + FLU*(EMAX-Emin)
             ERGmin(N) = Emin
             ERGMAX(N) = EMAX
             SUMM(N) = SUM
         GO TO 10
 20      CONTINUE
              DO I=1,NMAX !Normalize the cumulative function
              CUM(I) = SUMM(I)/SUMM(N)
              END DO
         CLOSE (LUNRD)
      END IF
```

0.000E+00	0.000E+00	0.000E+00	0.000E+00
1.000E-14	2.000E-13	0.000E+00	0.000E+00
2.000E-13	2.930E-13	0.000E+00	0.000E+00
2.930E-13	4.292E-13	0.000E+00	0.000E+00
4.292E-13	6.287E-13	0.000E+00	0.000E+00
6.287E-13	9.209E-13	0.000E+00	0.000E+00
9.209E-13	1.349E-12	0.000E+00	0.000E+00
1.349E-12	1.976E-12	0.000E+00	0.000E+00
1.976E-12	2.895E-12	3.469E-01	9.900E+01
2.895E-12	4.240E-12	2.959E-01	9.900E+01
4.240E-12	6.212E-12	2.460E-01	9.900E+01
6.212E-12	9.099E-12	3.542E-01	7.473E+01
9.099E-12	1.333E-11	2.552E-01	5.677E+01
1.333E-11	1.953E-11	1.809E-01	5.639E+01
1.953E-11	2.860E-11	3.535E-01	3.240E+01
2.860E-11	4.190E-11	2.223E-01	3.637E+01
4.190E-11	6.138E-11	3.069E-01	2.363E+01
6.138E-11	8.991E-11	3.334E-01	1.862E+01
8.991E-11	1.317E-10	3.111E-01	1.645E+01
1.317E-10	1.929E-10	2.538E-01	1.290E+01
1.929E-10	2.826E-10	2.811E-01	1.034E+01
2.826E-10	4.140E-10	2.135E-01	1.217E+01
4.140E-10	5.316E-10	1.495E-01	1.552E+01
5.316E-10	6.251E-10	1.770E-01	1.405E+01
6.251E-10	6.826E-10	1.443E-01	2.144E+01
6.826E-10	8.337E-10	1.483E-01	1.141E+01
8.337E-10	8.764E-10	1.467E-01	2.707E+01
8.764E-10	1.125E-09	1.600E-01	1.095E+01
1.125E-09	1.445E-09	1.069E-01	7.393E+00

Neutrons source: Source.f

```
*********************************************************************
*********************** Samplig from the Histogram *********
*********************************************************************
*** Select a random energy interval
      DUMMYSEED = PIPIPI
      C = CUM(N) * FLRNDM(DUMMYSEED)
*** Find interval (no need to check first interval CUM=0)
      DO I=2,N
        IF (CUM(I) .GT. C) THEN
***         Found interval I, select a random energy inside
            E = ERGmin(I) + (ERGMAX(I)-ERGmin(I))*FLRNDM(C)
            GO TO 90
        END IF
      END DO
*** It should never come here
      CALL FLABRT('SOURCE','C .GT. CMAX!')
 90   CONTINUE
*********************************************************************

*  Particle age (s)
      AGESTK (NPFLKA) = +ZERZER
      AKNSHR (NPFLKA) = -TWOTWO
*  Kinetic energy of the particle (GeV)
      TKEFLK (NPFLKA) = E
*  Particle momentum
*      PMOFLK (NPFLKA) = PBEAM
      PMOFLK (NPFLKA) = SQRT ( TKEFLK (NPFLKA) * ( TKEFLK (NPFLKA)
     &                       + TWOTWO * AM (IONID) ) )
*  Cosines (tx,ty,tz)
      CALL RACO ( TXX, TYY, TZZ )
      TXFLK  (NPFLKA) = TXX
      TYFLK  (NPFLKA) = TYY
      TZFLK  (NPFLKA) = TZZ
*     TZFLK  (NPFLKA) = SQRT ( ONEONE - TXFLK (NPFLKA)**2
*    &                       - TYFLK (NPFLKA)**2 )
*  Polarization cosines:
      TXPOL  (NPFLKA) = -TWOTWO
      TYPOL  (NPFLKA) = +ZERZER
      TZPOL  (NPFLKA) = +ZERZER
*  Particle coordinates
      XFLK   (NPFLKA) = XBEAM
      YFLK   (NPFLKA) = YBEAM
      ZFLK   (NPFLKA) = ZBEAM
```



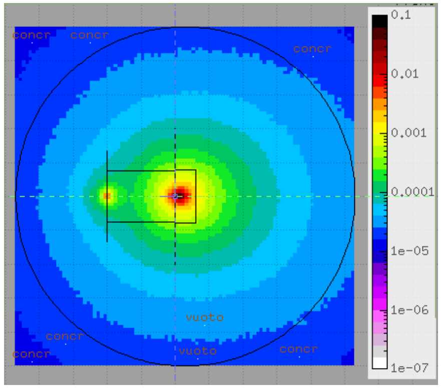


Validation of the neutrons source

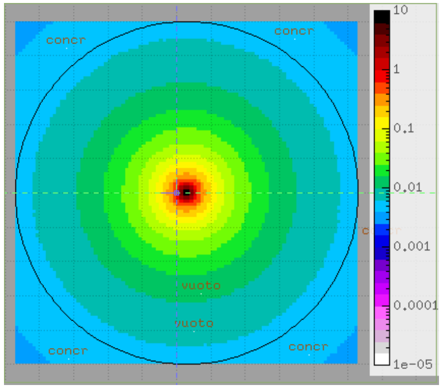
Activation study in a simplified geometry (a concrete sphere surrounding the target) after an irradiation of 1h at 1 μA

- Source:16.5 MeV Proton Beam
- Primary particles: $1x10^{10}$ protons (~$4x10^{7}$ neutrons)
- Simulation time: 1 day and 16 hours

- Source: neutrons isotropic point source
- Primary particles: $1x10^{9}$ neutrons
- Simulation time: 45 min



VS



Nuclide	Protons as primary particles Bq	Uncertainty (%)	Neutrons as primary particles Bq	Uncertainty (%)	Variance
^{28}Al	2.97E+07	0.3	2.97E+07	0.1	0.1%
^{39}Ar	7.11E-01	0.6	7.05E-01	0.1	0.7%
^{41}Ca	2.09E-03	0.7	2.10E-03	0.1	0.4%
^{31}Si	3.84E+05	0.7	3.85E+05	0.1	0.4%
^{24}Na	1.13E+05	1.0	1.13E+05	0.2	0.4%
^{27}Mg	1.44E+06	1.3	1.45E+06	0.3	0.8%
^{56}Mn	5.33E+05	1.8	5.28E+05	0.4	0.8%
^{29}Al	6.95E+05	1.9	7.05E+05	0.3	1.6%

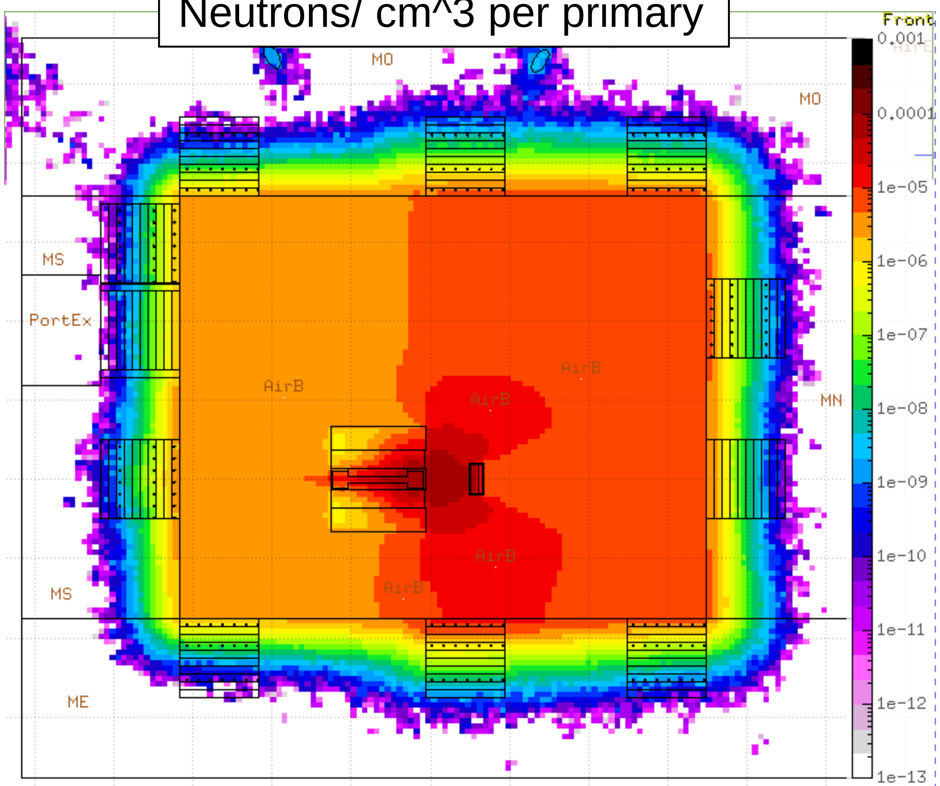
Results

~ 5×10^{11} **protons**

Production rate ~ 4×10^{-3} neutrons/proton

Primary particles:
2×10^{9} neutrons simulated

Neutrons/ cm^3 per primary



- Processor: i7-4790
- N° core: 4 (8 thread)
- N° runs: 8
- N° cicle: 5

Simulation Time: 20 hours

(instead of 50 days)

Results

Principal long-lived radionuclides have been found for different life expectancy of the cyclotron:

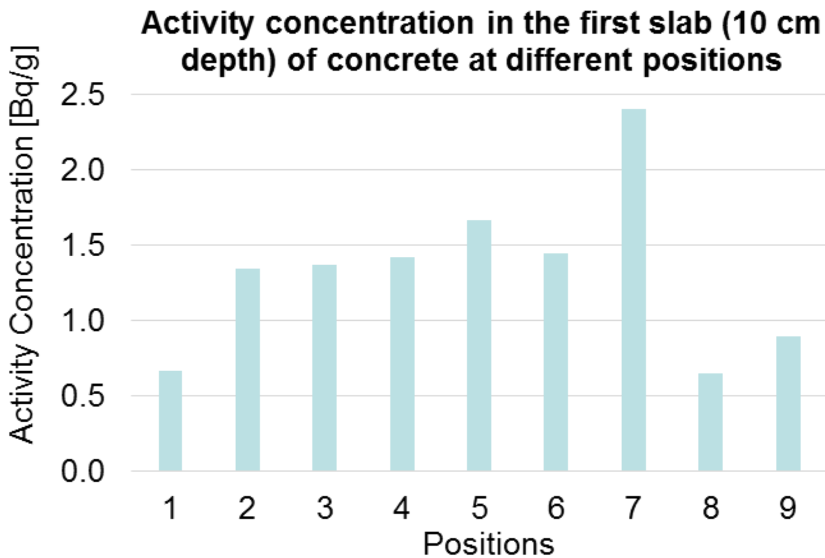
- In concrete

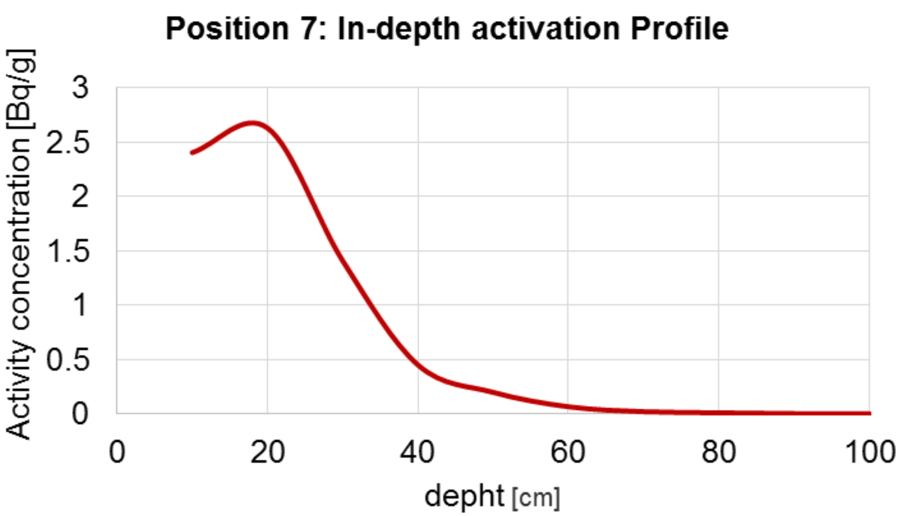
Nuclide	T1/2	Max Activity Concentration (Bq/g)		Uncertainty (%)
		10 years	20 years	
^{55}Fe	2.73 y	2.80	3.02	0.5
^{152}Eu	13.537 y	1.50	2.41	1.2
^{60}Co	5.2714 y	0.29	0.36	2.6
^{154}Eu	8.593 y	0.12	0.17	3.6
^{54}Mn	312.3 d	0.07	0.07	1.9
^{134}Cs	2.0648 y	0.04	0.04	5.1
^{3}H	12.3 y	0.02	0.03	8.4

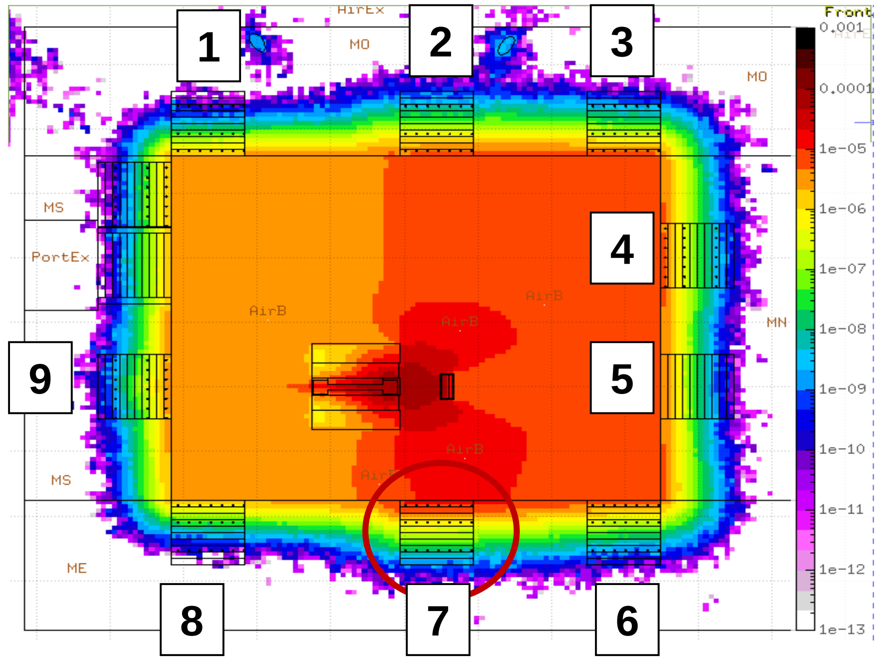
- in reinforcement rods

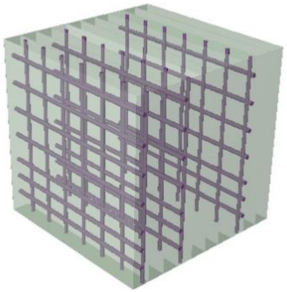
Nuclide	T1/2	Max Activity Concentration (Bq/g)		Uncertanty (%)
		10 years	20 years	
^{55}Fe	2.73 y	81.70	88.15	0.2
^{63}Ni	100 y	3.71	7.18	0.2
^{60}Co	5.2714 y	3.10	3.93	1.9
^{54}Mn	312 d	2.70	2.71	0.7

^{152}Eu in concrete after 20 years of cyclotron operation

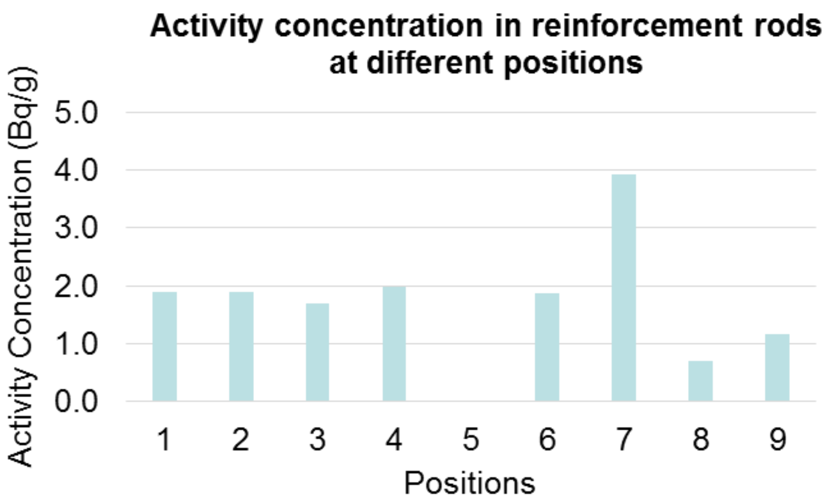


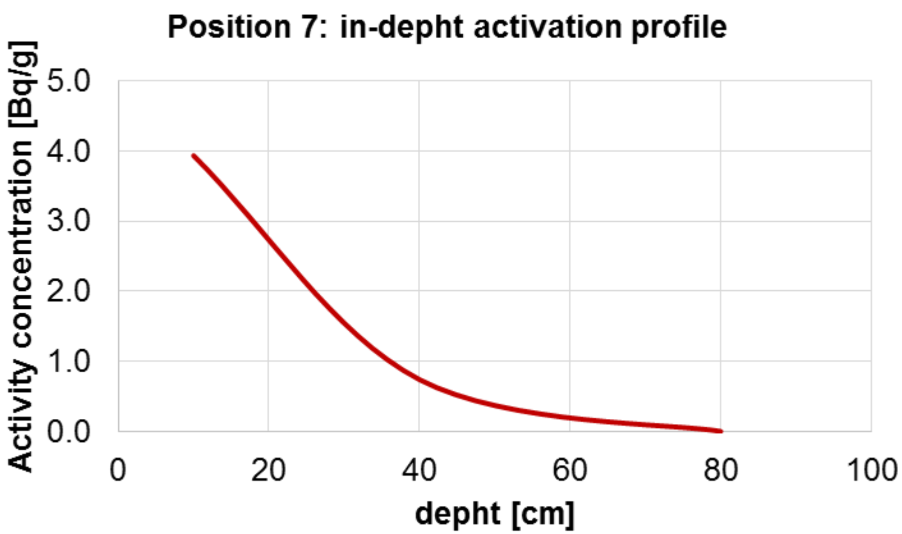


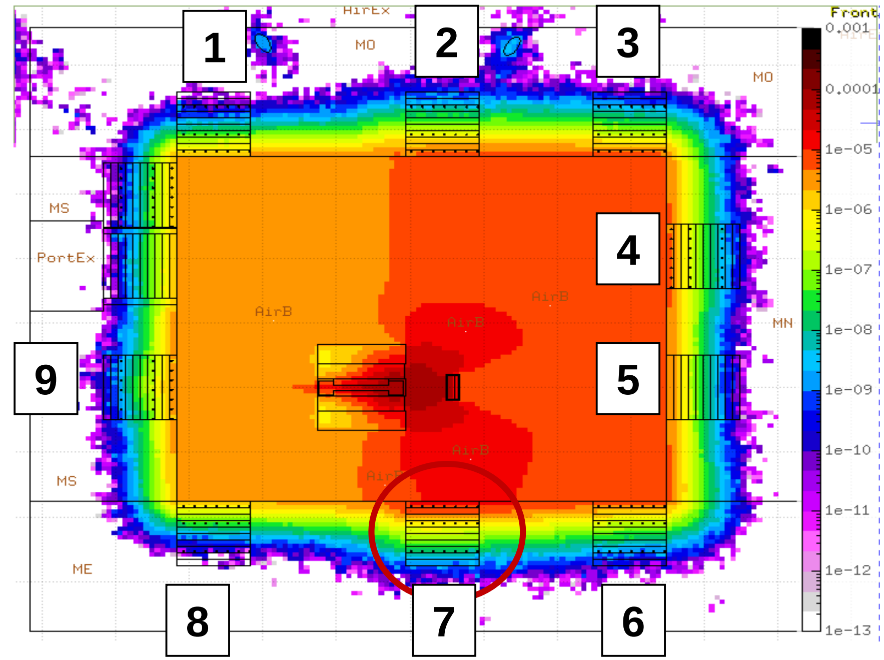


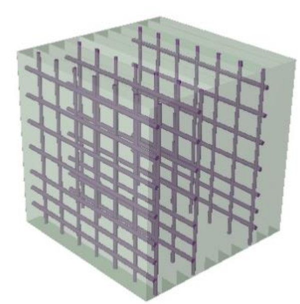


^{60}Co in reinforcement rods after 20 years of cyclotron operation









Conclusions

- provided a detailed model is developed, Monte Carlo approach to the study of bunker activation level allows to characterize with satisfactory accuracy the radioactive waste from the decommissioning of a cyclotron facility.

- In particular, Monte Carlo simulations allow to reproduce more accurately, compared to analytical methods, the real geometry of the bunker and to obtain reliable results in the case of “bad geometry” conditions.

- A preliminary evaluation of radioactive waste allows to identify any critical issue and possible countermeasures to be taken in order to decrease future dismantling costs. This also allows, during the construction phase of a new cyclotron site, performing an optimal design of the whole site and to define ad-hoc decommissioning strategies.

Ongoing Projects

Experimental validation of the MC model

Thank you!