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# DESIGN AND RADIATION PROTECTION OF HOSPITAL CYCLOTRON FACILITIES

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# Outline

Planning the installation of a cyclotron

- Shielding evaluation
  - radiations of interest
  - source terms
  - primary shielding
  - ducts and penetrations
- Activation
  - internal structures
  - Air
- Analytical vs. Monte Carlo approach
- Safety equipment & fault tree analysis
  - Risk analysis
  - fault tree analysis
  - staff entrapment
  - safety systems
  - Accident analysis
- Operational radiation protection
  - access to the bunker
  - ordinary maintenance
  - activity delivery

# References


• Technical Report No. 283 “Radiological safety aspects of the operation of proton accelerators”. IAEA, Vienna, 1988.

• NCRP Report No. 144 “Radiation Protection Design Guidelines for 0.1 - 100 MeV Particle Accelerator Facilities”. (Rev of NCRP 51). NCRP, Bethesda, 2004.

• Tecdoc 1211 “Charged particle cross section data base for medical radioisotope production: diagnostic radioisotopes and monitor reactions”. IAEA, Vienna, 2001)

• Safety Standards Series WS-G-2.2 “Decommissioning of Medical, Industrial and Research Facilities”, IAEA,Vienna, 1999.

• ICRP Publication 76 “Protection from Potential Exposures: Application to Selected Radiation Sources”. ICRP, Oxford, 1997.

•IAEA TRS 471 “Cyclotron produce radionuclides: guidelines for fetting up a cyclotron facility”. IAEA, Vienna, 2009.

# State of the art PET cyclotrons

| Manufacturer | Model | Particles | Energy (MeV) | Variable energy | Beam current (µA) | Type of Ion source | N. of targets |
|---|---|---|---|---|---|---|---|
| IBA | Cyclone KEY | H- | 9.2 | N | 80 | Int. PIG | 3 |
| IBA | Cyclone 18/9 | H- (D-) | 18 (9) | N | 150 (65) | Int. PIG | 8 |
| IBA | KIUBE | H- | 18 | Y | >200 | Int. PIG | 8 |
| IBA | IKON | H- | 30 | Y | >500 | Ext. Cusp | 3 ports per side, one of which dedicated to PET can fit up to 5 targets |
| IBA | Cyclone 30 XP | H- (D-) (α) | 30 (15) (30) | Y | 400 (50) (50) | Ext. Cusp | 2 ports, can fit beam lines and target stations |
| IBA | Cyclone 70P | H- | 70 | Y | 750 | Ext. Cusp | 2 ports, can fit beam lines and target stations |
| IBA | Cyclone 70XP | H- (D-) (α) | 70 (30) (70) | Y | 750 (50) (50) | Ext. Cusp | 2 ports, can fit beam lines and target stations |
| GE | GENtrace | H- | 7.8 | N | 50 | Int. PIG | 3 |
| GE | MINITrace | H- | 9.6 | N | 50 | Int. PIG | 5 |
| GE | PETtrace | H- (D-) (α) | 16.5 (8.4) | N | 100 | Int. PIG | 6 |
| ACSI | TR19 | H- (D-) | 19 (9) | Y | > 150 (100) | Ext. Cusp | 2 ports, each can fit up to 4 targets |
| ACSI | TR24 | H- | 25 | Y | up to 750 (300) | Ext. Cusp | 2 ports, can fit beam lines and target stations |
| ACSI | TR24FLEX | H- (D-) | 30 (15) | Y | up to | Ext. Cusp | 2 ports, can fit beam lines and target stations |
| ACSI | TR30 | H- (D-) | 30 (15) | Y | > 750 (50) | Ext. Cusp | 2 ports, can fit beam lines and target stations |
| Sumitomo | Cypris HM12 | H- (D-) | 12 (6) | N | 100 (40) | Int. PIG | 2 ports, each can fit up to 4 targets / optionally 1 single port |
| Sumitomo | Cypris HM18 | H- | 18 | N | 400 | Int. PIG | 2 ports, each can fit up to 4 targets |
| Sumitomo | Cypris HM20 | H- (D-) | 20 (10) | N | 100 (50) | Int. PIG | 2 ports, each can fit up to 4 targets |
| NIIEFA Efremov | CC-12 | H- | 12 | N | 50 | Ext. Cusp | n.a. |
| NIIEFA Efremov | CC-18/9 | H. | 18 (9) | N | 100 /50) | Ext. Cusp | n.a. |
| NIIEFA Efremov | MCC-30/15 | H- (D-) | 30 (15) | Y | 500 (250) | Ext. Cusp | n.a. |

# Summary of relevant characteristics of modern PET cyclotrons

| | |
|---|---|
| Accelerated particles | $H^-$, optionally $D^-$ |
| Acceleration energy for H- | 10 - 20 MeV |
| Maximum extracted current | 50 - 150 μA |
| N. of installed targets | 5 - 8 |
| Max target current | 35 - 100 μA |
| Self shield | standard for $E_{max} \leq$ 11 MeV, opt. at higher energies |
| Dual beam | standard, at least for some target combination |

# Targets & nuclear reactions

| Nuclear reaction | Target material | Target volume | Target pressure | Target body |
|---|---|---|---|---|
| $^{18}O\ (p,n)\ ^{18}F$ | $H_2{}^{18}O$ | 1.5 - 3-0 $cm^3$ | 30 bar | Niobium |
| $^{18}O\ (p,n)\ ^{18}F$ | $^{18}O_2$ gas | 50 – 100 $cm^3$ | 10 bar | Aluminum |
| $^{20}Ne\ (d,\alpha)\ ^{18}F$ | Ne gas + 0.3 % $F_2$ | 60 $cm^3$ | 10 bar | Aluminum |
| $^{14}N\ (p,\alpha)\ ^{11}C$ | $N_2$ gas + 0.5 % $O_2$ | 80 $cm^3$ | 10 bar | Aluminum |
| $^{16}O\ (p,\alpha)\ ^{13}N$ | $H_2O$ | 1 $cm^3$ | 6 bar | Silver |
| $^{14}N\ (d,n)\ ^{15}O$ | $N_2$ gas + 1 % $O_2$ | 50 – 60 $cm^3$ | 10 bar | Aluminum |
| $^{15}N(p,n)^{15}O$ | $^{15}N_2$ gas + 1 % $O_2$ | 50 – 60 $cm^3$ | 10 bar | Aluminum |

# Cyclotron site planning: basic data

- type of cyclotron
  (acceleration characteristics: **type of particles, max energy & beam current**)

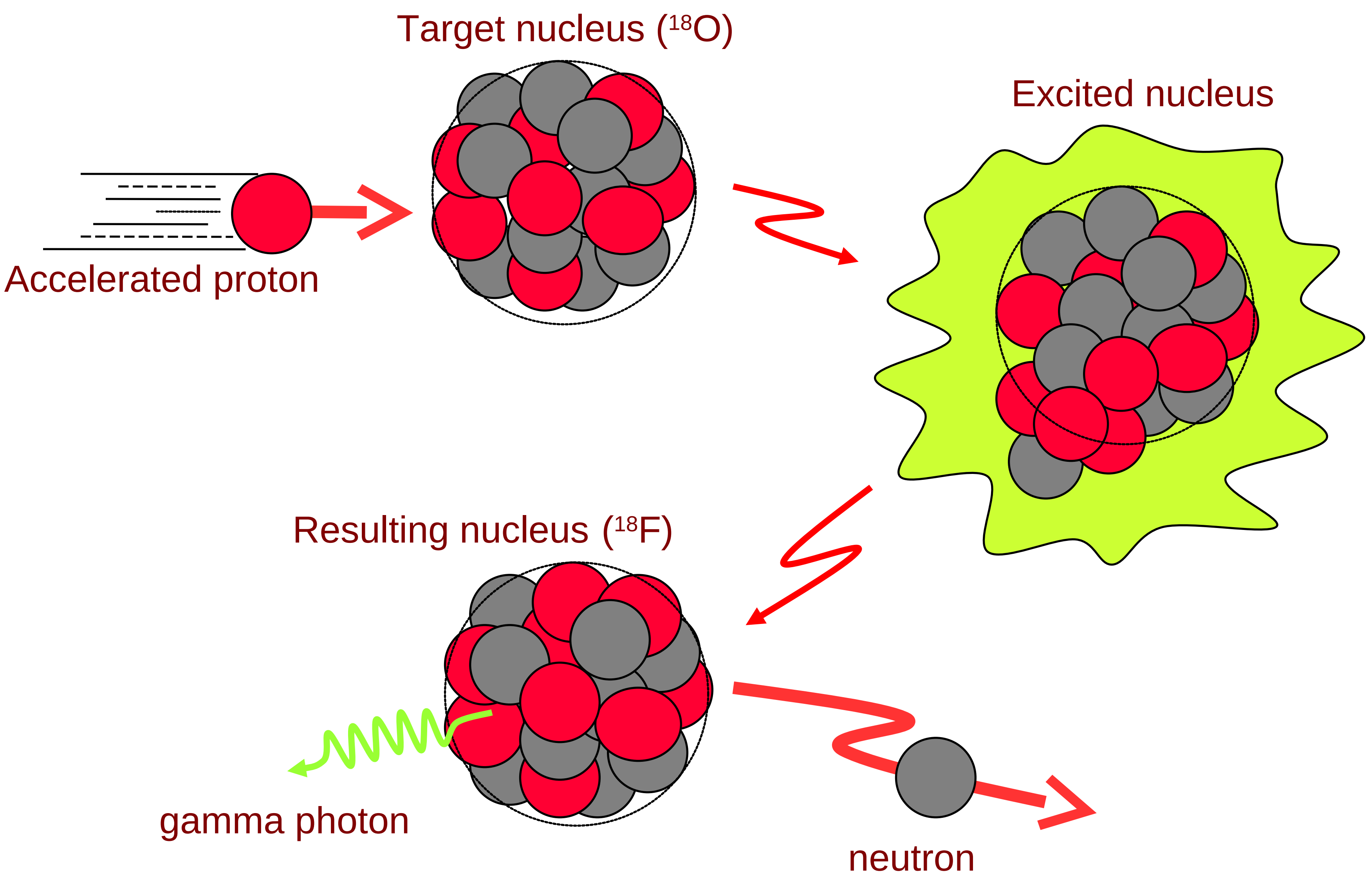
- nuclear reactions
  (production of secondary neutrons)

- targets type and position
  (max current on target)

- materials
  (taking into account activation characteristics)

- type of use and workload
  (working days/year, mix of production cycle, n. of irradiations, current, ...)

# The basis of the activation process



# Main components of radiation at a cyclotron

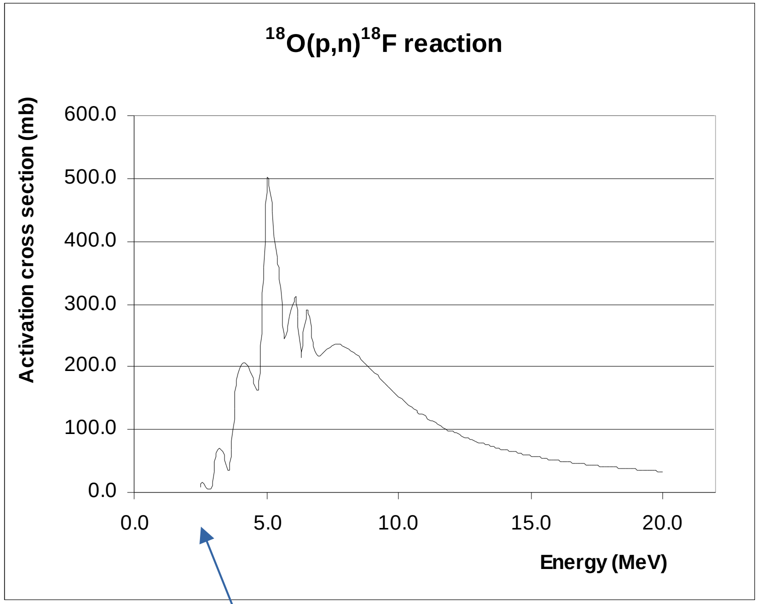
- Secondary neutrons from nuclear reactions
- Gamma rays resulting from the de-excitation of nuclei from the first excited levels after a nuclear reaction
- Gamma ray from the radionuclides produced in the desired reaction
- Gamma ray from other activated materials

In most cases, neutrons are the most important radiation and are of primary interest in shielding calculations.

The shielding necessary for the neutrons is sufficient to attenuate the gamma as well.

However, in the case of self-shielded cycltrons, the major dose component emerging from the self-shielded can be gammas

# Neutrons energy




Considering the production of $^{18}F$:

The threshold energy of the $^{18}O(p,n)^{18}F$ reaction is 2.4 MeV
Bomabrding with protons of 18 MeV, the maximum neutron energy will be

$E_{n\ max} = 18 - 2.4 = 15.6\ MeV$

Hovewer, most neutrons will have a much lower energy, according to a spectral distribution.

# Neutron spectra

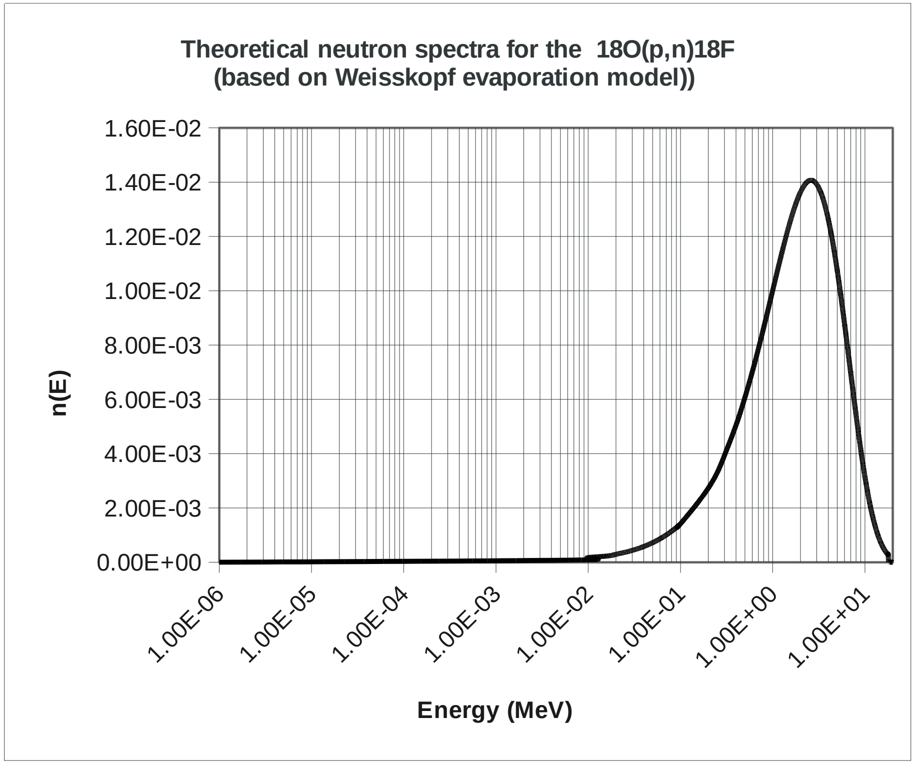
Neutrons produced in nuclear reactions in the range of energy of interest for PET radionucldies are emitted according to a model of “evaporation”, as describer by Weisskopf (Phys Rev, 52, 1937). This produces a maxwellian distribution:

$$N(E)d(E) = a \cdot E \cdot e^{(-E/T)}$$

Where:

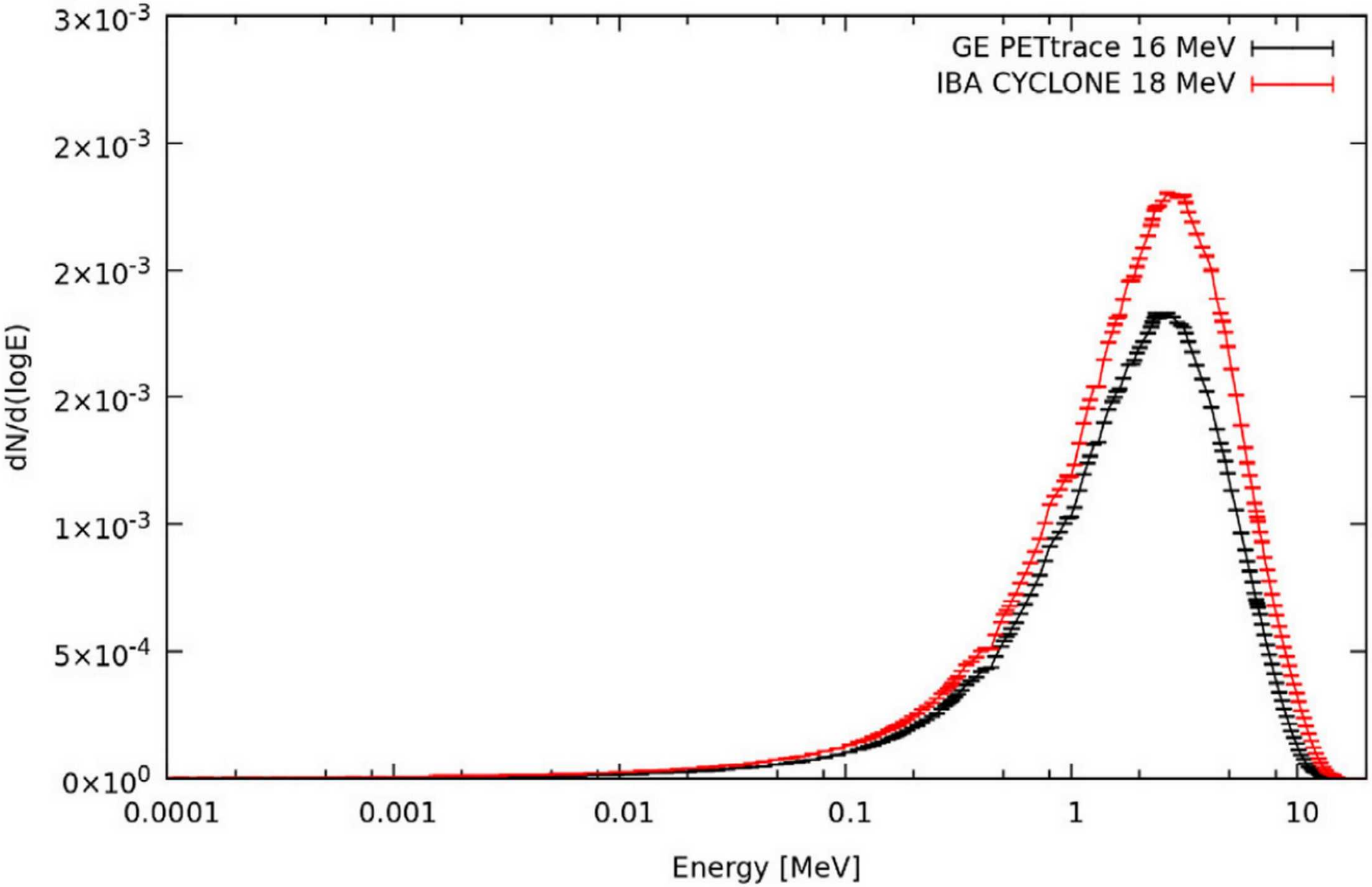
*a* is a multiplicative constant, which value is 0.05 – 0.2 MeV

*T* is the so called “temperature” parameter”. For $^{18}F$ it is ~ 2.6 MeV



# Neutron spectra

For the necessity of shielding calculation, the theortical approximation of the spectra is sufficient. Nevertheless, using Monte Carlo simulations with a detailed model of the target and materials, it is possible to obtain a more precise spectra.



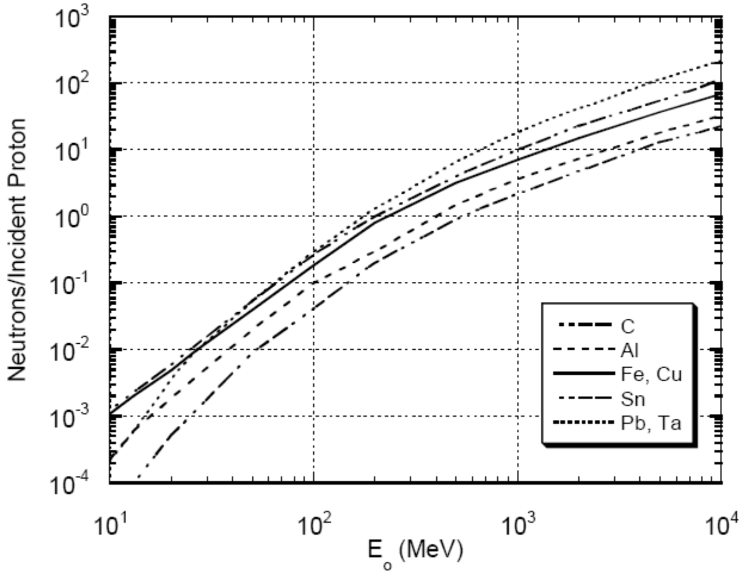

From Vichi, https://doi.org/10.1016/j.radphyschem.2020.108966

# Neutron yield

...but how many neutrons are produced ?

The cross section of the desired nuclear reaction can guide us, but it does not accounts for other reactions, form neutrons arisign from beam interaction on the collimators, the body of the target and other components.

The NCRP 144 Report (mostly based on Tesch data of 1985 and 1986) gives graphs that allow to estimate the number of neutron produced for incident proton in materials like Carbon, Aluminum, Copper, Iron, relating thus to the beam current in μA




Alternatively, MC simulations or information by the cyclotron manufacturer can be used to gather the *n/p* number (typically $2 \cdot 10^{-3} – 7 \cdot 10^{-3}$ , depending on the proton energy, cycltron and target type and material)

$$N_{protons} = \frac{I_{beam} \cdot 10^{-6}}{1.602 \cdot 10^{-19}}$$

| | | |
|---|---|---|
| Beam current on target | 60.00 | microA |
| Number of incident protons | 3.75E+14 | p/sec |
| Yield of neutron per proton n/p | 5.00E-03 | n/p |
| Total number of neutron produced | 1.87E+12 | n/sec |

# Source terms: neutrons angular distribution

- Depending on the type of cyclotron (target position), there could be a preferential direction for neutrons emission

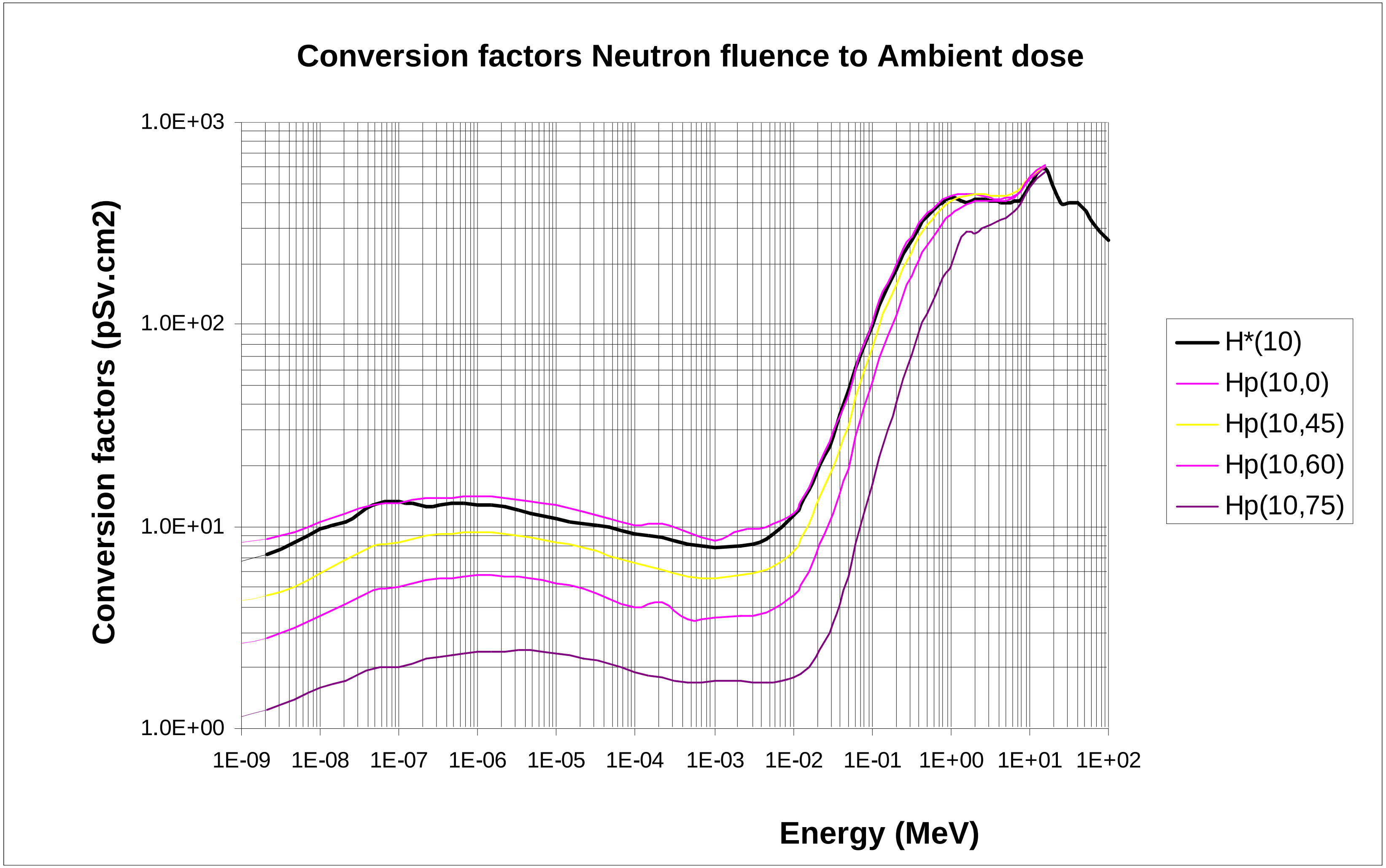
- In the past, NCRP51 on the basis of data gathered in the ‘60s and ‘70s on cyclotrons with energy > 30 MeV, suggested a factor Y(90°) / Y(0°) $\leq$ 0.1

- Measurements on modern cyclotrons in the PET energy range and interpretation of data reported by NCRP 144 show a substantially isotropic angular distribution.

- The above conclusion is in agreement with the model of evaporation emission

- Moreover, it has to be considered the position of the targets ! In most models of cyclotron, there are at least 2 preferential directions, in many targets are distributed all around the system.

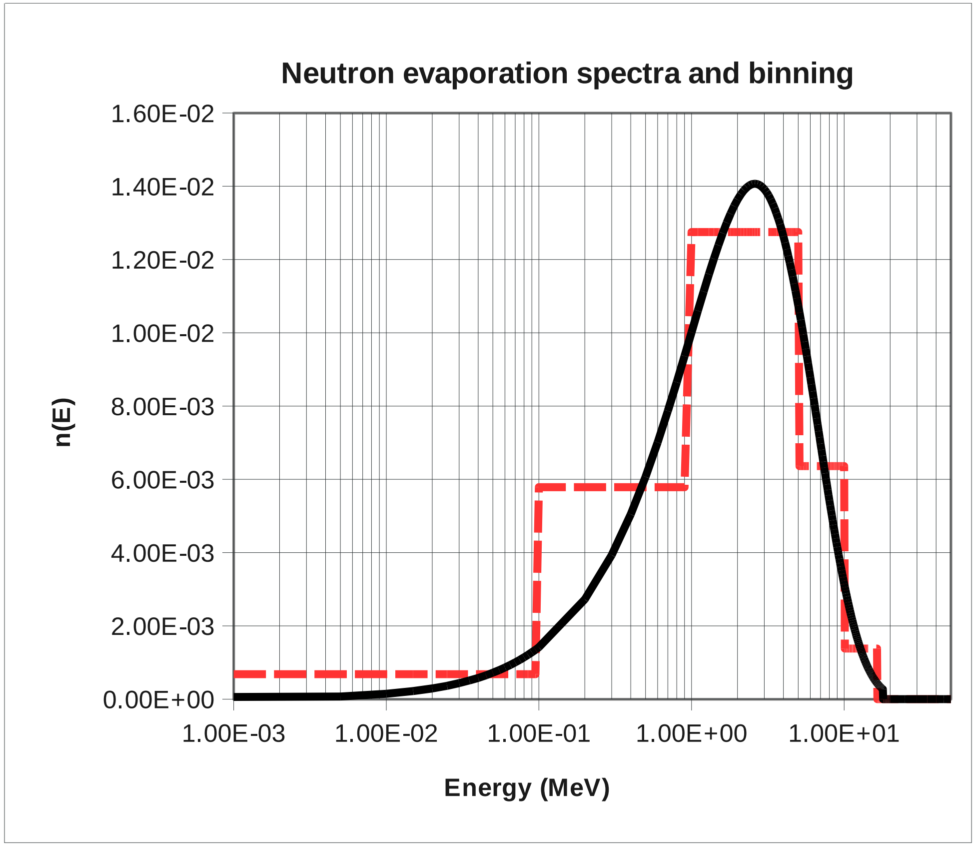
*Infantino A et al.  Phys Med. 2016 Dec;32(12):1602-1608*




The conversion factor from neutron fluence to dose rate changes significantly as a function of energy

IAEA TecRep 403 "Compedium of neutron spectra and detector resposnes for radiation protection purposes". Vienna, 2001

# Selecting the average dose conversion factor



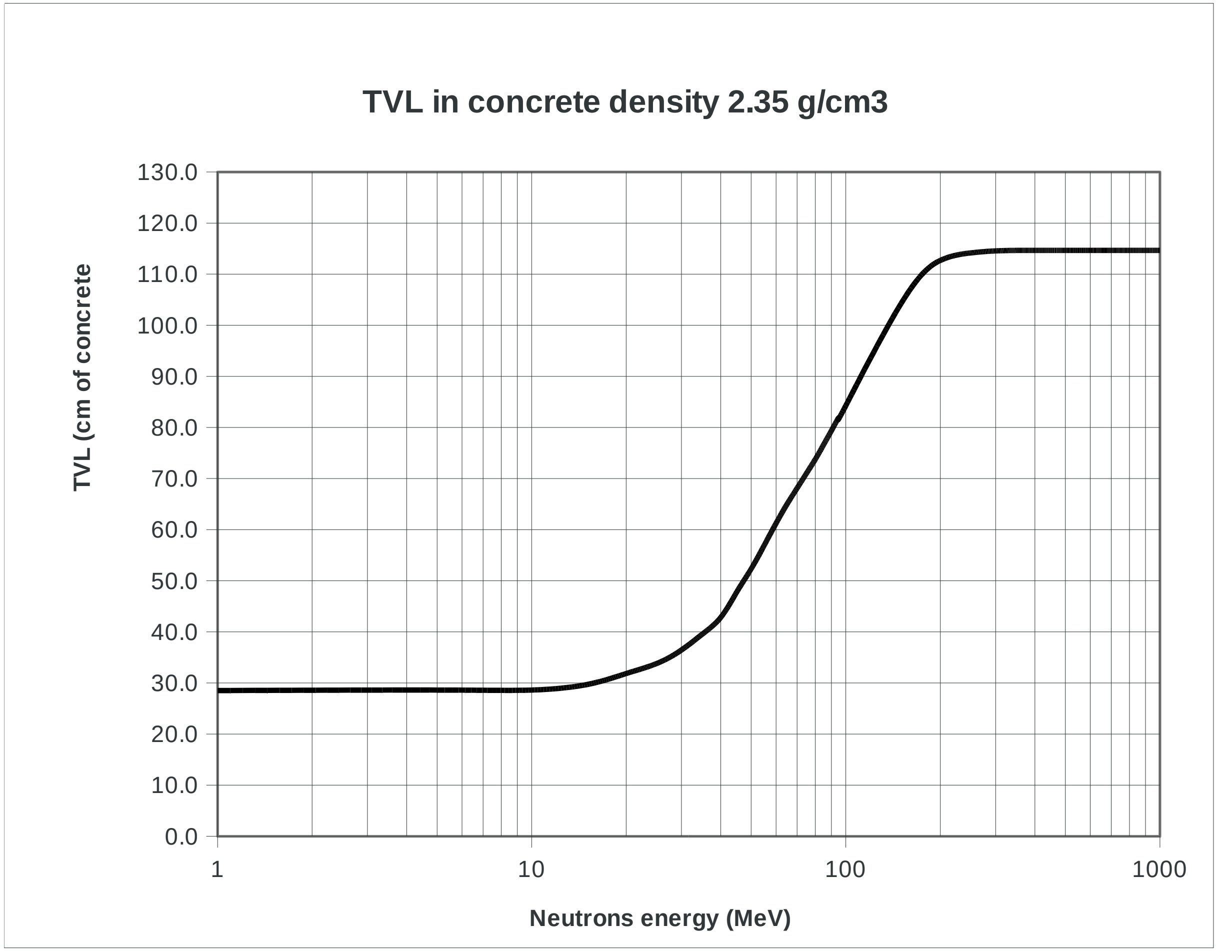

Ideally, it should be made a convolution between the neutron spectra distribution and the curve of the conversion factor.

In practice, binning the spectra in a limited number of intervals and adopting the average conversion factor within each interval gives an acceptable weighted average.

# Evaluation of the reference dose rate inside the bunker

| | | |
|---|---|---|
| Punctual flux of neutrons produced in the target | 1.87E+12 | n/s |
| Reference distance | 100 | cm |
| Surface of the sphere centered on the target | 1.26E+05 | cm2 |
| Fluence at the reference distance | 1.49E+07 | n/cm2.s |
| Average dose factor assumed | 400 | pSv.cm2 |
| Ambient dose rate at reference distance Href | 2.14E+04 | mSv/h |
| | 21.4 | Sv/h |

This level of dose is REALLY dangerous !




IAEA TecRep 283 pag. 218, FermiLab Report pag. 98, NCRP 144 pag. 171

In the range of energies of interest the TVL for concrete are 28 – 35 cm

# Gamma radiation

- prompt gamma radiation from excited nuclei (2 – 6 MeV)
- capture gamma (n,$\gamma$) form H nuclei (2.2 MeV)
- delayed gamma from activated materials (mainly 0.51 MeV; in general, < 2MeV)
- The TVL for this complex of radiation is < 25 cm concrete.

| | | |
|---|---|---|
| Specific gamma ray constant | 1.40E-04 | mSv/h per MBq at 100 cm |
| Activity produced | 1.85E+05 | MBq |
| | | |
| Resulting dose rate | 25.9 | mSv/h at 100 cm |

Within the bunker of the cyclotron, the dose due to the PET radionuclide produced is not significant, compared to the neutron dose

# Dose constraints for shielding

Dose limits, as recommended by ICRP and set out in the IAEA BSS and international (e.g. EU Directive 2103/59) and national regulations, represent the upper boundary of risk to which workers and population can be exposed.

The design of medical facilities should be made aiming to the goal of keeping the doses to workers and members of the public as low as reasonably achievable (taking into account social and economic), according to the ALARA principle.

This means that design criteria should be optimized, in order to ensure that the radiation exposure of workers and members of the public is well below the dose limits.

Dose constraints are thus introduced as a tool for optimization, and should be adopted at every step of the design of radiation protection, in particular in the calculation of shielding.  The values for dose constraints adopted in the calculation of shielding may vary, according to local regulations.

The following Table reports a the interval of values that are generally adopted:

| **Category** | **Dose constraint (mSv/y)** |
|---|---|
| Exposed workers | 1.0 – 6.0 |
| Non exposed workers and public | 0.3 – 1.0 |

# Equations for shielding estimate with the TVL method

$$H_{expected} = H_{ref} \cdot \frac{U \cdot T}{d^2}$$

Basic equation for estimate of the expected dose at the target point; it is based on a reference dose value (at a certain angle and at a distance of 1 m); in general, $H_{ref}$ could be different at 0° and 90°.

$$B_x = \frac{H_{limit}}{H_{expected}}$$

Required attenuation factor

$$n = \log_{10}\left[\frac{1}{B_x}\right]$$

Number of TVL required to obtain the requested attenuation

$$S_p = TVL_1 + (n-1) \cdot TVL_n$$

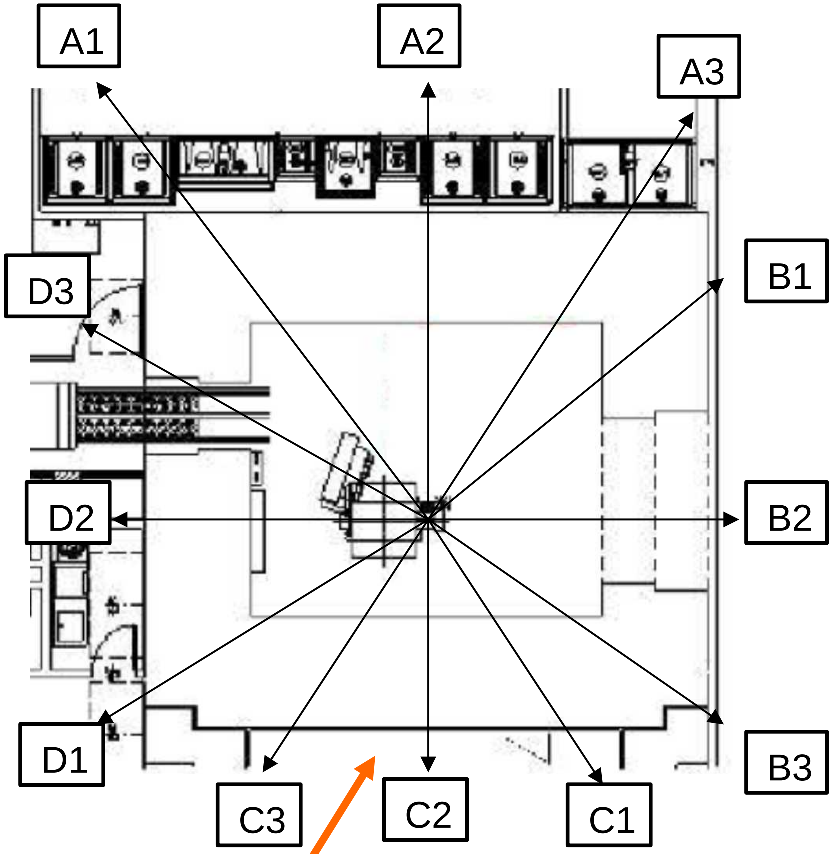
Shielding thickness calculated taking into account different values for the first and “equilibrium” TVL

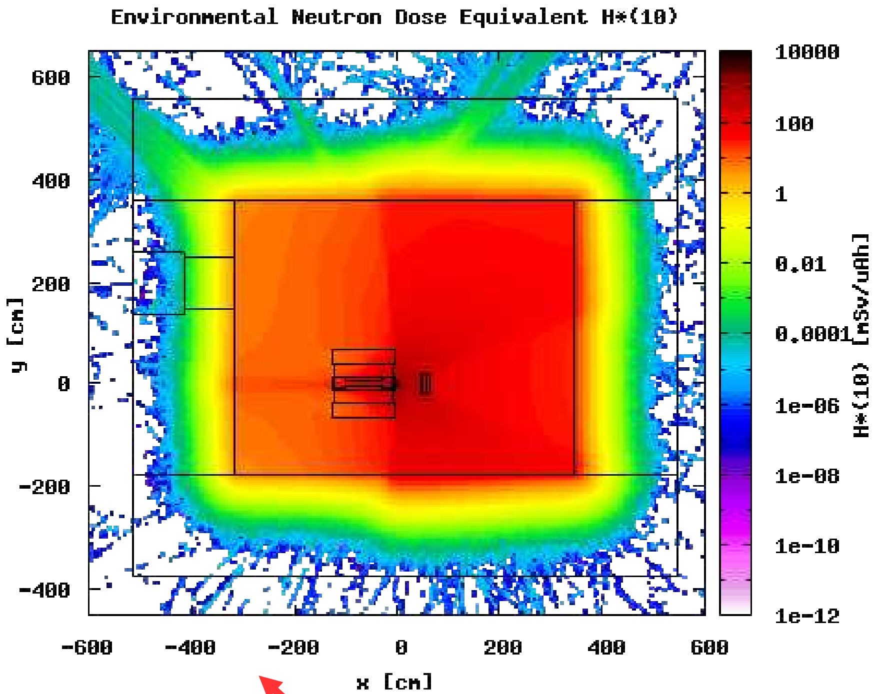
$$S_{p,s} = S_p + HVL_n$$

Final shielding thickness, with the addition of a “safety” HVL

# Calculation of cyclotron shielding:

## Analytical vs. Monte Carlo approaches



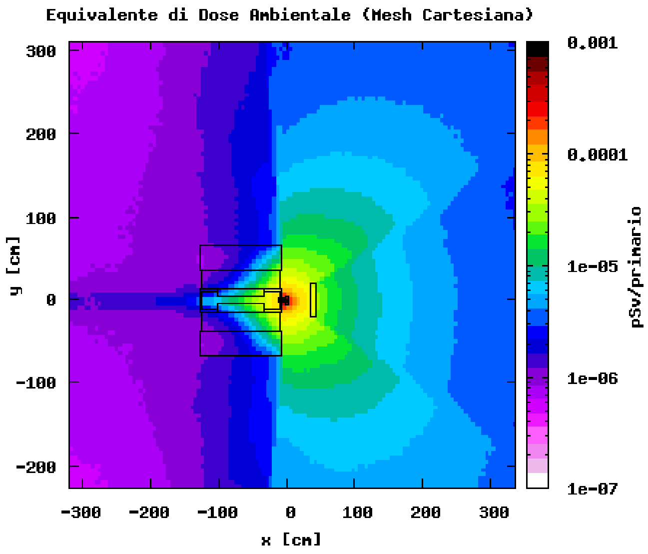



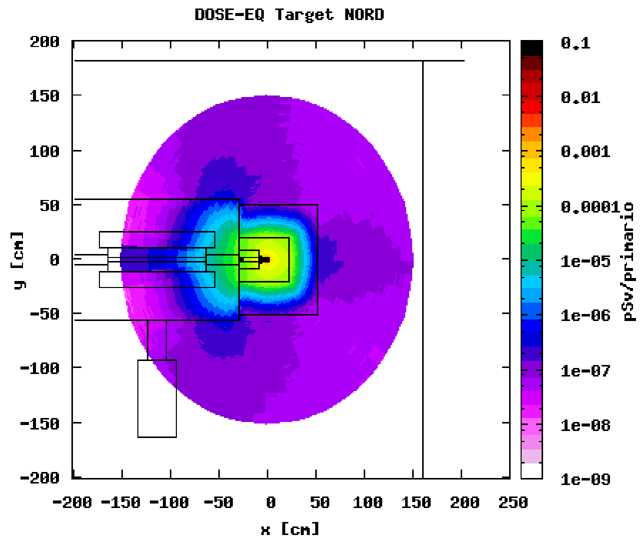

Analytical: relatively simple calculation, for a limited number of sampling points, based on many assumption and approximations.

Monte Carlo: complex calculation, based on a model (accurately) describing the real geometry and considering all the components at once

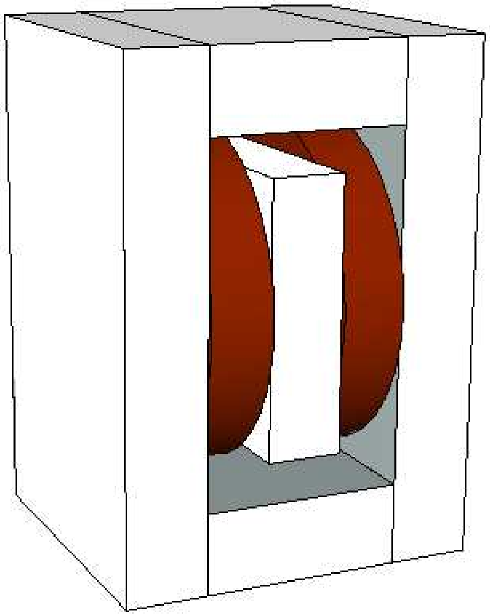
# Source terms: role of Monte Carlo simualtions

- Monte Carlo simulations make possible to obtain, in reasonable computing time, accurate source terms at reference distance and angluar distributions, taking into account absorption and diffusion from the cyclotron structure
- the Monte Carlo model of a specific type of cyclotron should always be enough accurate to reproduce the geometry and materials
- a validation of the model against measured data is necessary …



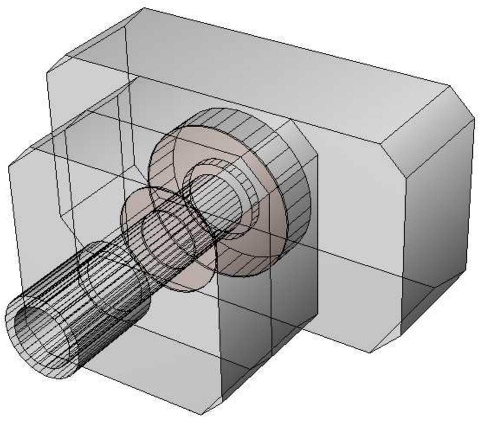



# Use of Monte Carlo methods to simulate real geometry



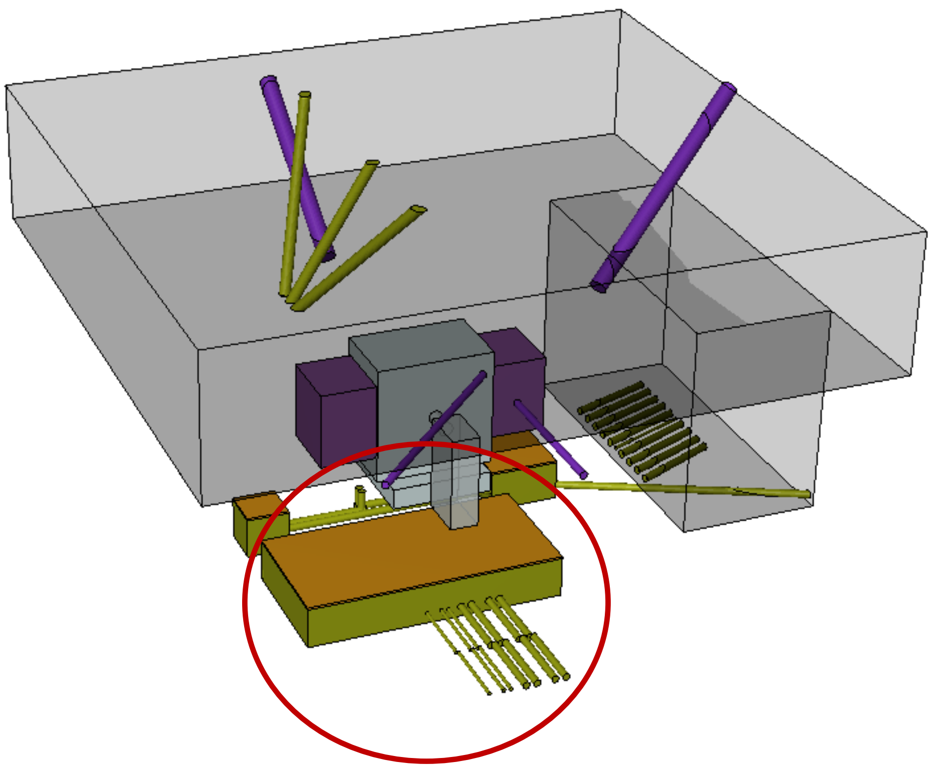
3D Monte Carlo model of the
PETtrace cyclotron
(GE Healthcare, Uppsala, Sweden)

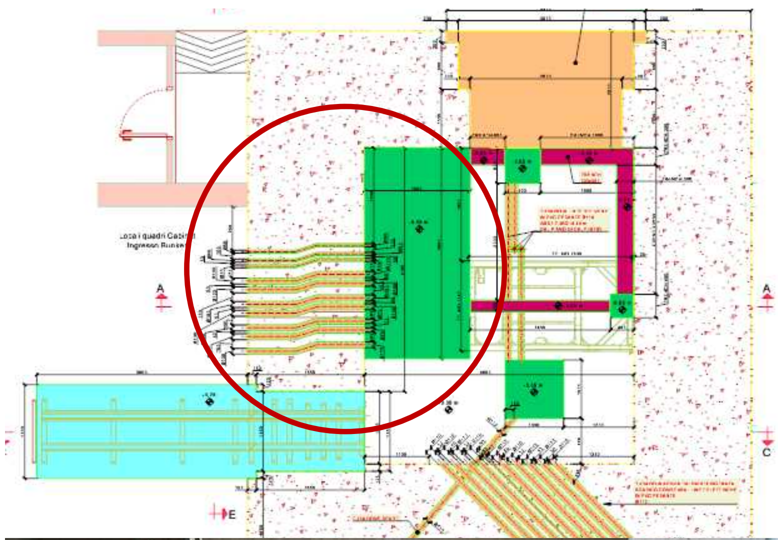
3D Monte Carlo model of the $^{18}F^{-}$ target
(GE Healthcare, Uppsala, Sweden)



*Infantino A et al.  Phys Med. 2016 Dec;32(12):1602-1608*

# MC planning of ducts and penetrations

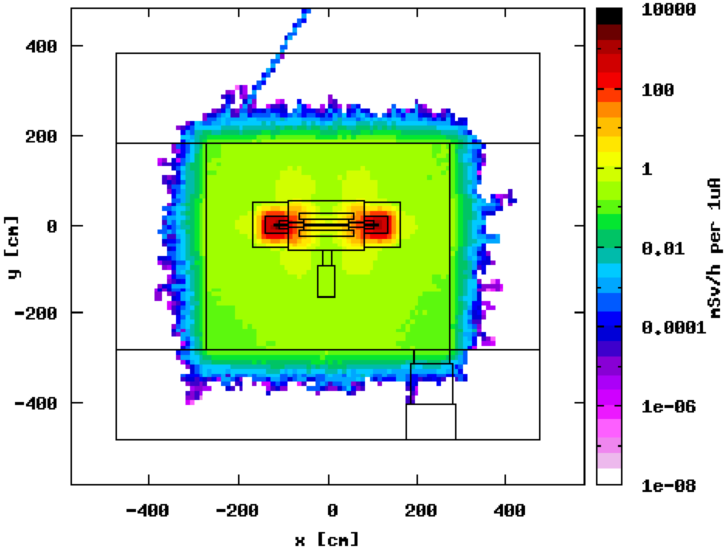


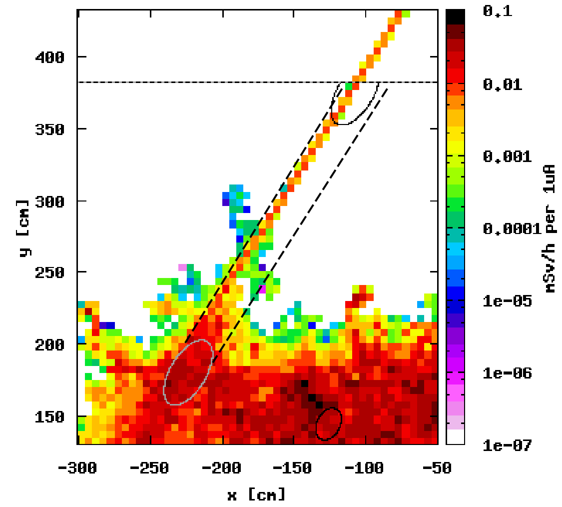


Detail of the floating floor, the walls and the pipes containing the delivery lines, the RF cables, the control cables, etc.

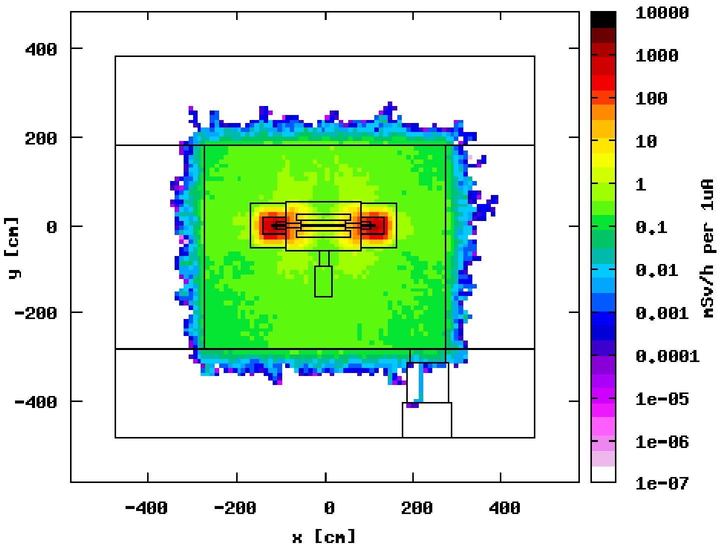
*Infantino A. et al. Radiation Physics and Chemistry, Volume 116, p. 231-236. 2015*

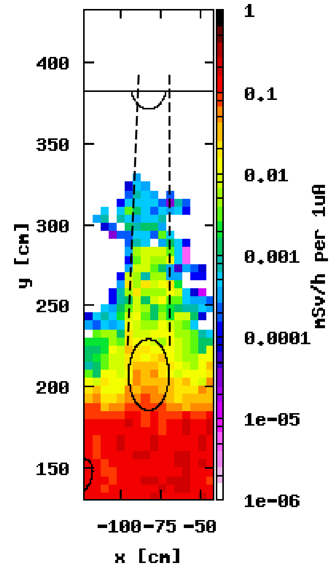
# Example use of MC results in the optimization of design




First version of the penetration design




Final version of the optimized penetration design

*Infantino A. et al. Radiation Physics and Chemistry, Volume 116, p. 231-236. 2015*

# Cyclotron structures activation

All the metallic structure witihin the bunker will be activated, at least to some extent.

The components of the cycltron are cleary more subjecy to activation form the protons of the beam, as well as from secondary neutrons.

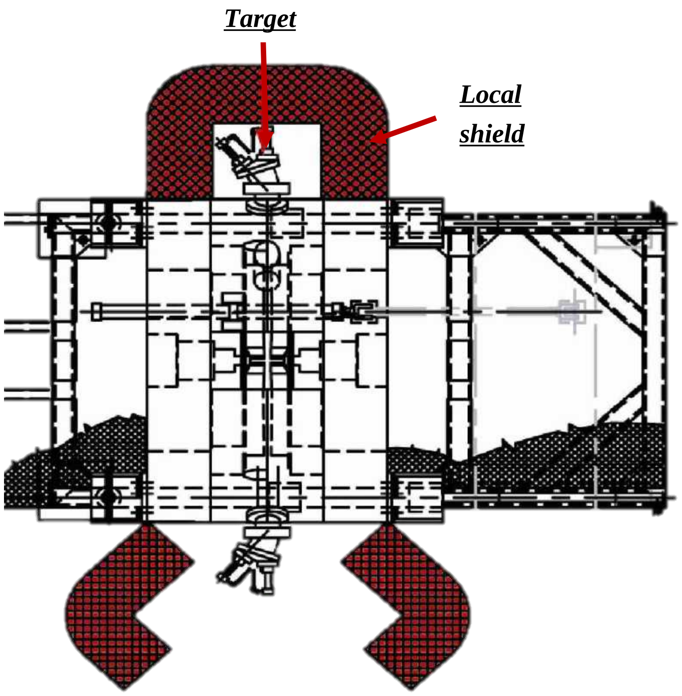
| Radionuclide | $T_{1/2}$ | Reaction | Decays to |
|---|---|---|---|
| $^{56}Co$ | 78.8 days | $^{56}Fe(p,n)^{56}Co$ | $^{56}Fe$, stable |
| $^{57}Co$ | 271.7 days | $^{56}Fe(p,g)^{57}Co$<br>$^{57}Fe(p,n)^{57}Co$ | $^{56}Fe$, stable |
| $^{58}Co$ | 70.8 days | $^{58}Fe(p,n)^{58}Co$ | $^{58}Fe$, stable |
| $^{51}Cr$ | 27.7 days | $^{50}Cr(n, g)^{51}Cr$ | $^{57}Cr$, stable |
| $^{54}Mn$ | 312.2 days | $^{54}Fe(n,p)^{54}Mn$ | $^{54}Cr$, stable |
| $^{52}Mn$ | 5.6 days | $^{52}Cr(p,n)^{52}Mn$ | $^{52}Cr$, stable |
| $^{56}Mn$ | 2.6 hours | $^{56}Fe(n,p)^{56}Mn$<br>$^{55}Mn(n,g)^{56}Mn$ | $^{56}Fe$, stable |
| $^{48}V$ | 16.0 hours | $^{48}Ti(p,n)^{48}V$ | $^{48}Ti$, stable |
| $^{59}Fe$ | 44.6 hours | $^{58}Fe(n,g)^{59}Fe$ | $^{59}Co$, stable |
| $^{24}Na$ | 15.0 hours | $^{27}Al(n,a)^{24}Na$<br>$^{23}Na(n,g)^{24}Na$ | $^{24}Mg$, stable |
| $^{24}Na$ | 15.0 hours | $^{27}Al(n,a)^{24}Na$ | $^{24}Mg$, stable |
| $^{28}Al$ | 2.2 minutes | $^{27}Al(n,g)^{28}Al$ | $^{28}Si$, stable |
| $^{64}Cu$ | 12.8 hours | $^{63}Cu(n,g)^{64}Cu$ | $^{64}Ni$, $^{64}Zn$, stable |
| $^{63}Zn$ | 38.0 minutes | $^{63}Cu(p,n)^{63}Zn$ | $^{63}Cu$, stable |
| $^{181}W$ | 120.9 days | $^{181}Ta(p,n)^{181}W$ | $^{181}Ta$, stable |
| $^{182}Ta$ | 115.0 days | $^{181}Ta(n,g)^{182}Ta$ | $^{182}W$, stable |
| $^{178}Lu$ | 28.4 minutes | $^{181}Ta(n,a)^{178}Lu$ | $^{178}Hf$, stable |

# Cyclotron structures activation

| Isotope | T1/2 | Expected Activity after 10 years in operation [Bq] |
|---|---|---|
| 3H | 12.33 y | 1,38E+006 |
| 8Li | 0.8 s | 7,47E+004 |
| 10Be | 1.5E6 y | 3,11E+000 |
| 12B | 0.03 s | 1,36E+005 |
| 14C | 5730 y | 9,71E+000 |
| 13N | 7.1 s | 2,29E+006 |
| 36Cl | 3.01E5 y | 2,13E+002 |
| 38Cl | 37.2 min | 1,50E+004 |
| 39Ar | 239 y | 4,86E+005 |
| 40K | 1.27E9 y | 2,26E-001 |
| 41Ar | 109.3 min | 5,40E+004 |
| 42K | 12.36 h | 2,89E+006 |
| 51Cr | 27.7 d | 2,51E+006 |
| 53Mn | 3.74E6 y | 2,07E+000 |
| 53Fe | 8.51 min | 7,76E+003 |
| 54Mn | 312.3 d | 9,72E+007 |
| 55Cr | 3.5 min | 1,32E+004 |
| 55Fe | 2.73 y | 2,56E+008 |
| 56Mn | 2.58 h | 4,72E+007 |
| 57Mn | 85 s | 5,68E+005 |
| 58Mn | 3 s | 1,85E+003 |
| 59Fe | 44.5 d | 9,84E+006 |

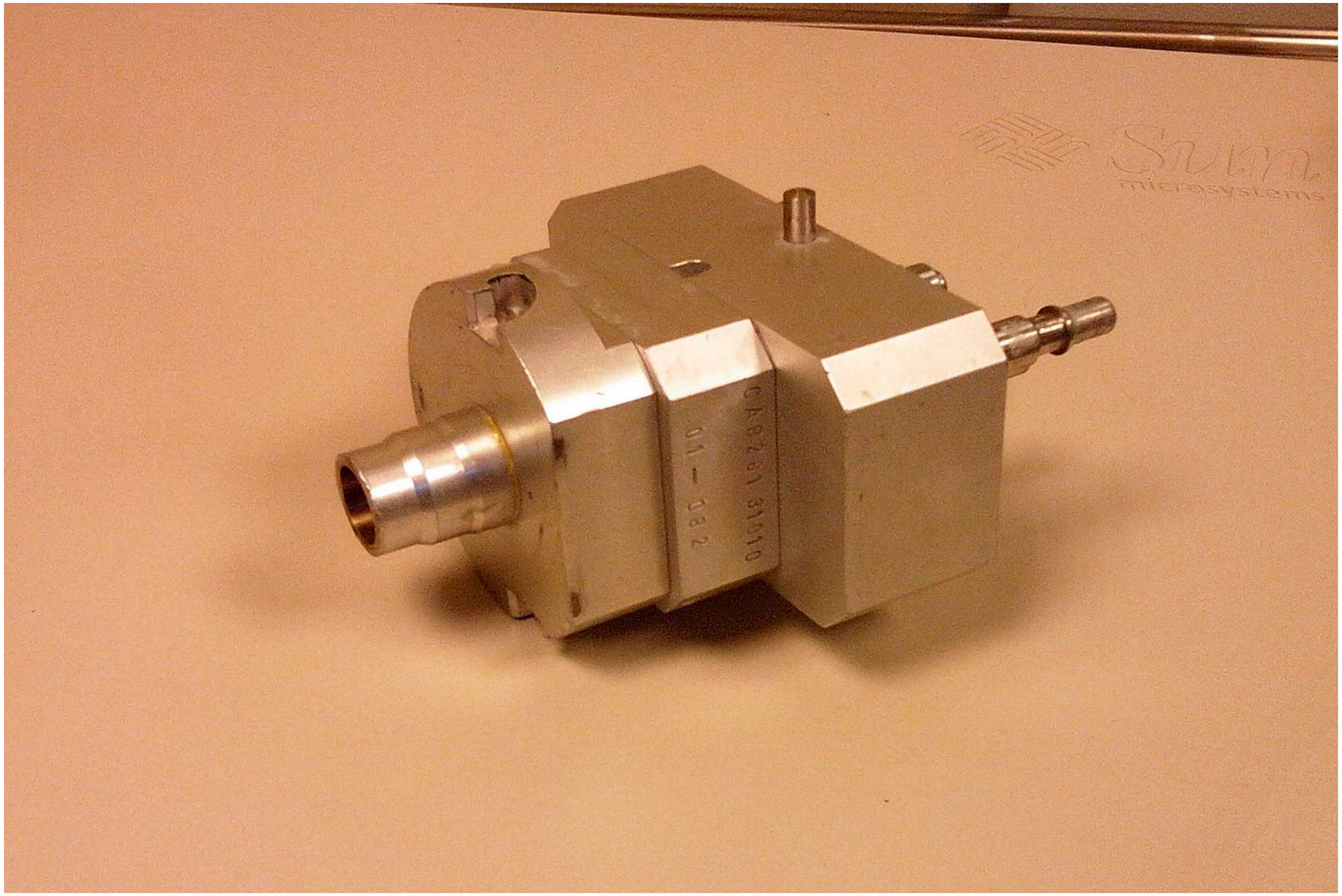
MC simulations allow to evaluate the perspective activation at the end of the useful life of the system.

In this example, it is assessed the activation of local shields (EOB) after 10 years in operation considering a workload of 2000 h/y and a maximum current of 100 μA.




*Infantino A. et al. Radiat Prot Dosimetry. 2017 Apr 1;173(1-3):185-191.*

# Example of typically activated components

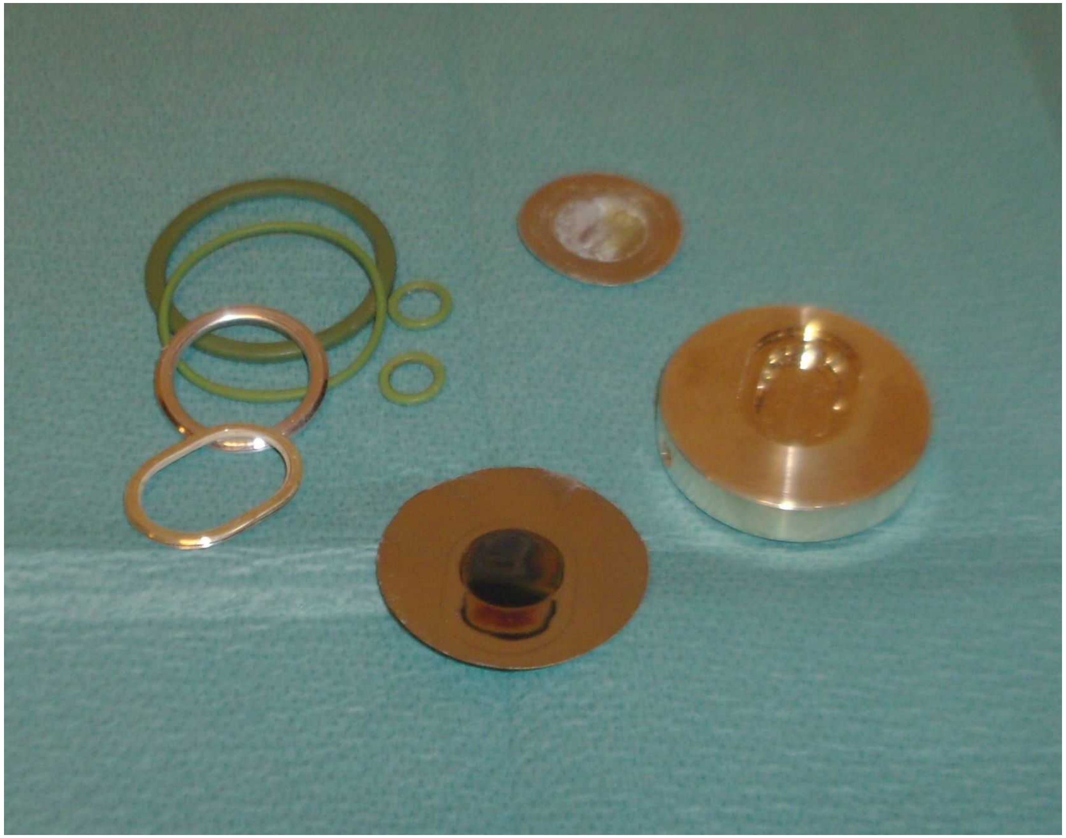


Target bodies are activated; most of activation is in the foils.

During maintenance, targets should be removed, to reduce the dose in proximity of the cycltron.

Targets at the end of their operation life are radioactive waste.

# Example of typically activated components



Target foils, gaskets and target chamber.

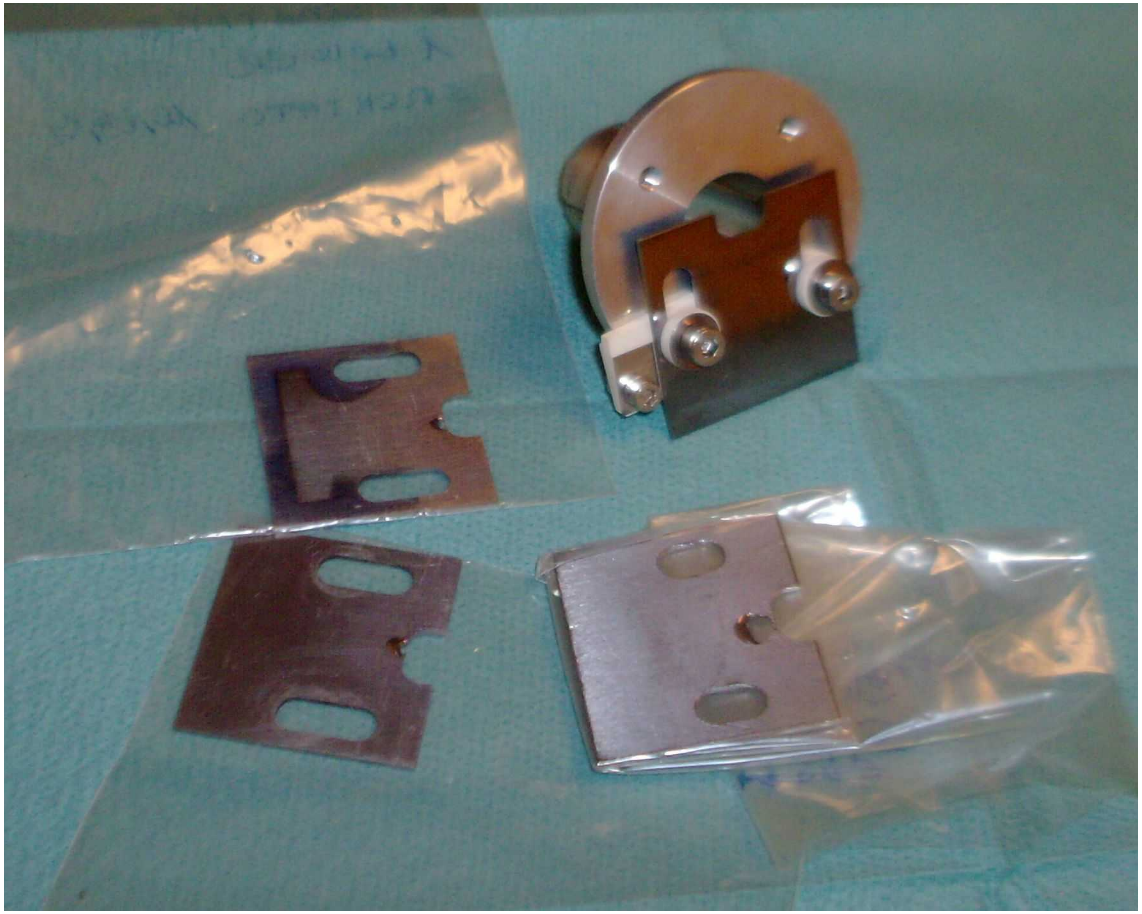
Foils are significantly activated and are one of the most typical radiactive waste at a cyclotron site; however, they are of limited volume

# Example of typically activated components

In line filters

Valves in the target filling stations

# Example of typically activated components



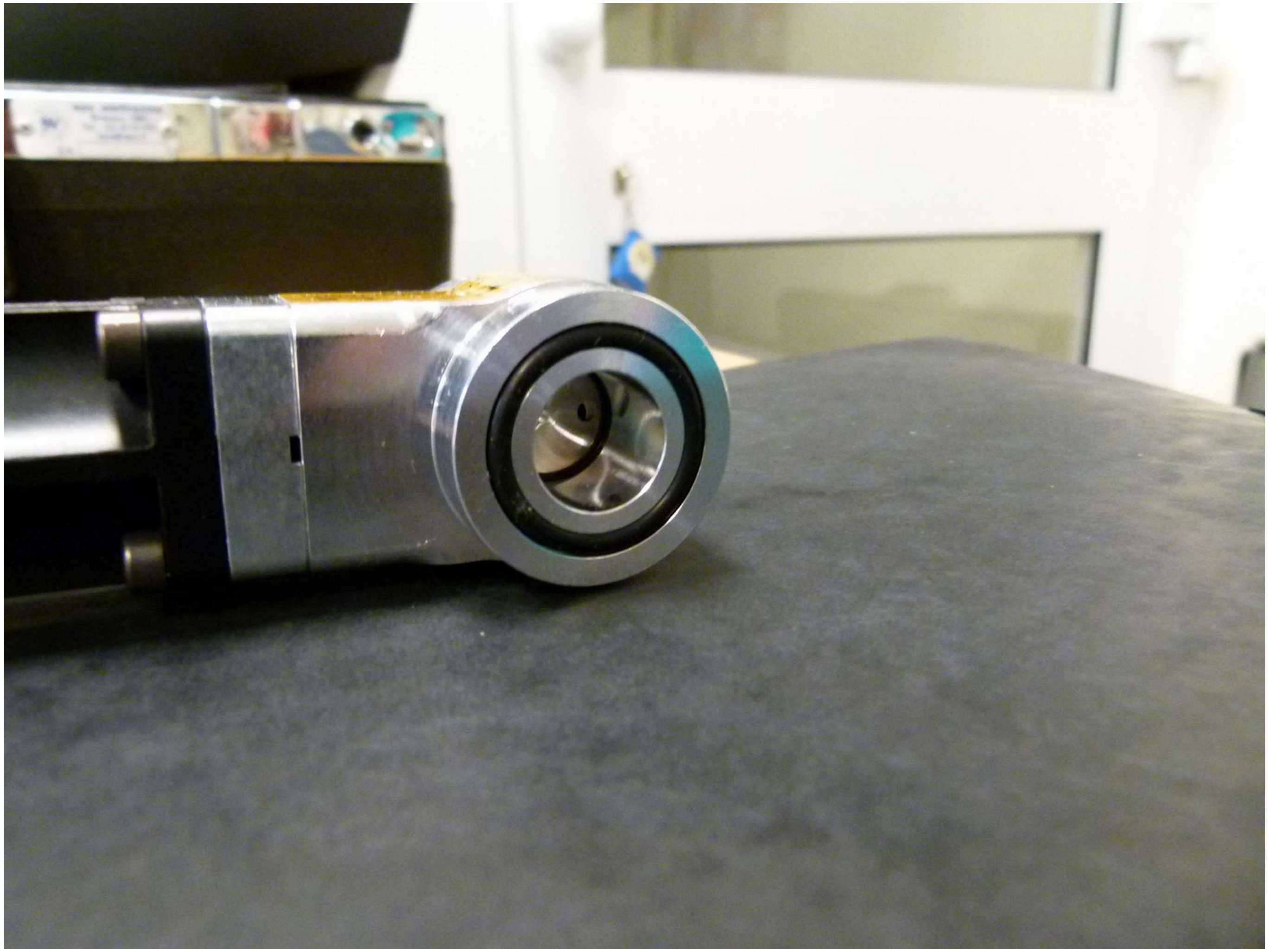
Collimatators in Tantalum are highly activated ( $^{181}Ta(p,n)^{181}W$ , $T_{1/2}$ =121 days).
Activation in Graphite collimators is only for short term.

# Example of typically activated components

Gate valves (also termed as Beam Exit Valves) are activated, since they can be hit by the “tails” of the beam.

When replaced they are radioactive waste.

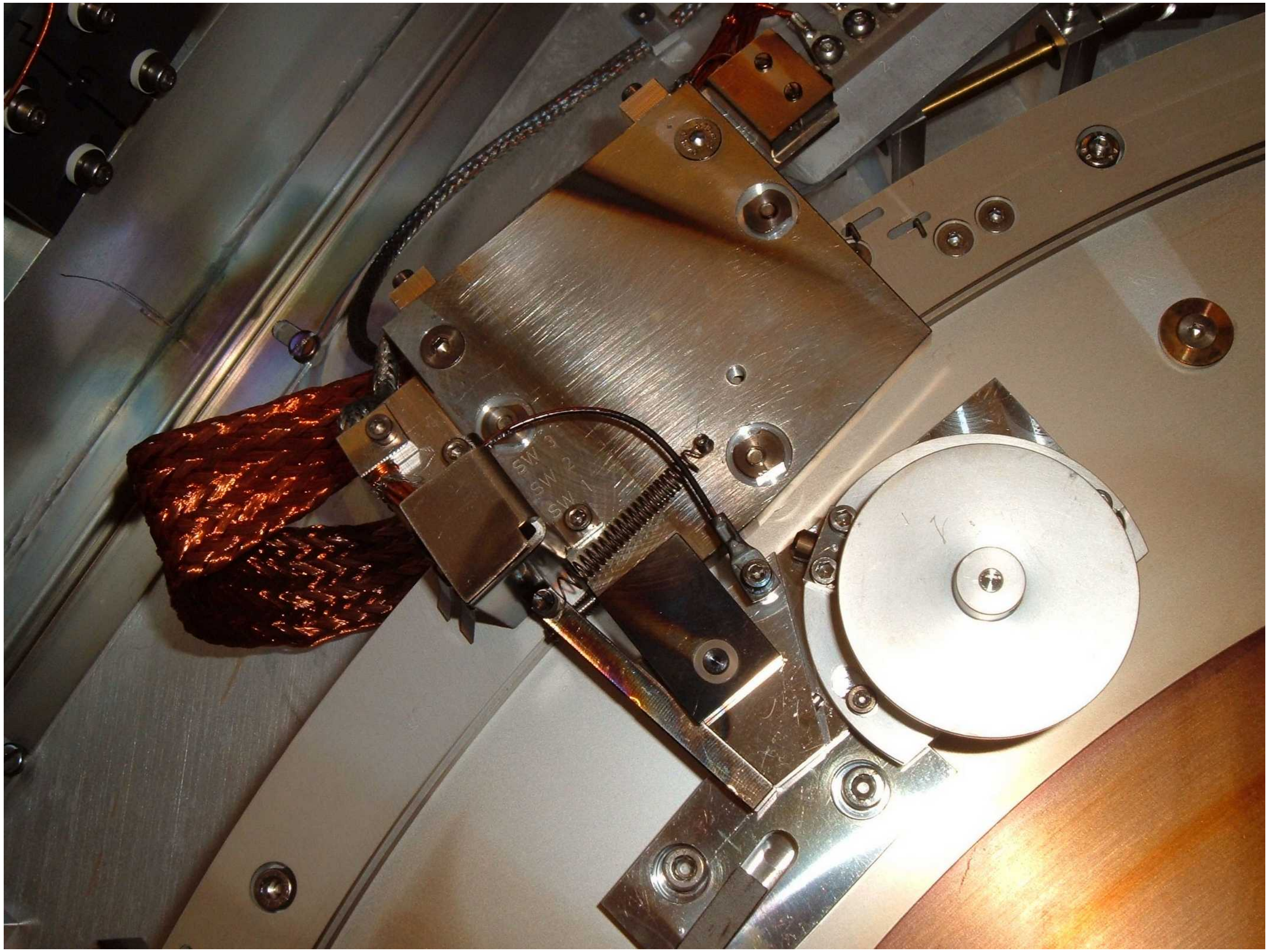
# Example of typically activated components



Gate valves (also termed as Beam Exit Valves) are activated, since they can be hit by the “tails” of the beam.

When replaced they are radioactive waste.

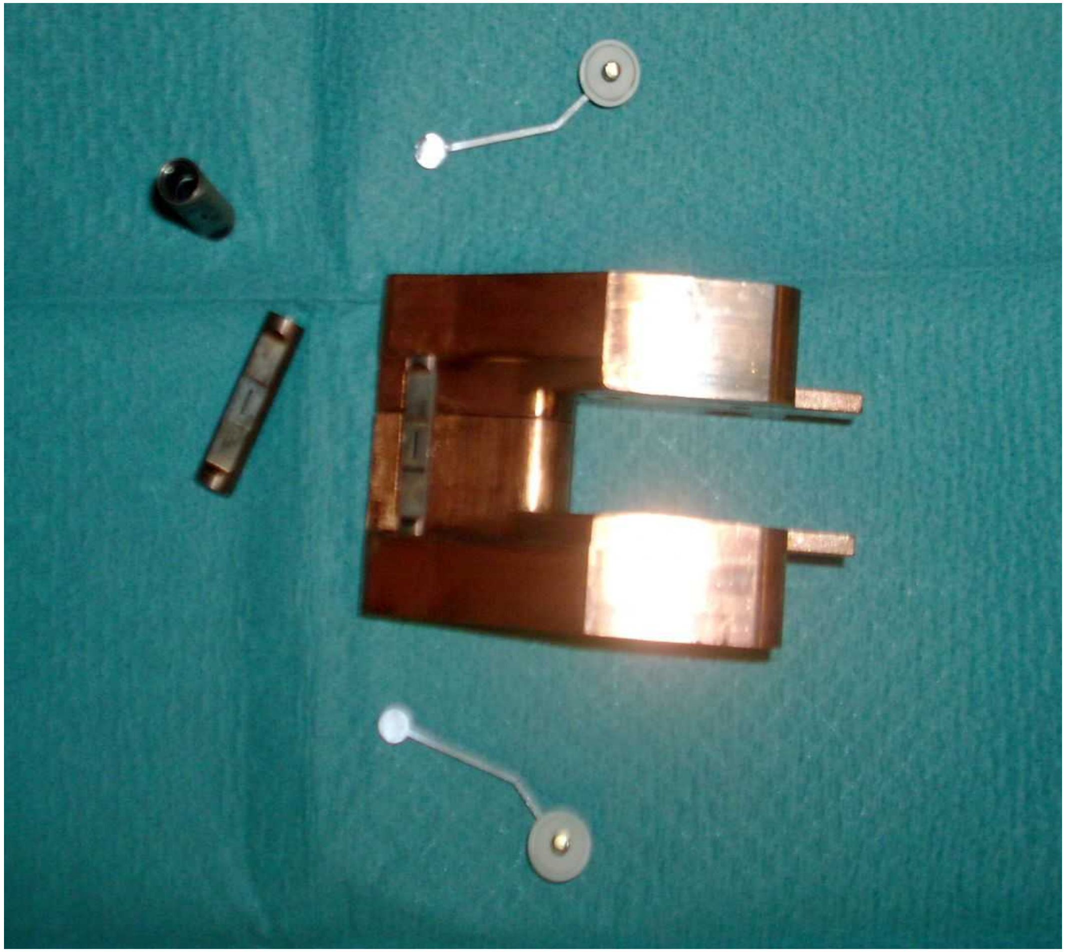
# Example of typically activated components




Stripping foils and all the componets of the extraction are activated.

During maintenance the carousels should be removed, to reduce the dose when operating inside the acceleration chamber of the cycltron.

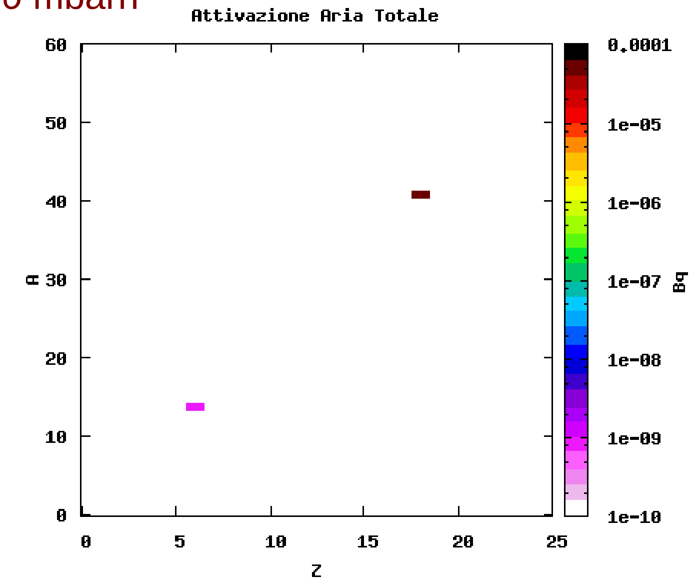
# Example of typically activated components



The deposits on the ion source body come from tantalum, the main component of the cathodes, and contain $^{182}Ta$, due to the (n, gamma) reactions in $^{181}Ta$, induced by the secondary neutrons produced in the reactions of the beam with the target and the collimators.

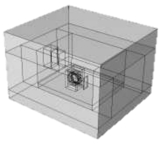
# Air activation

- $^{14}N(n,2n)^{13}N$ from fast neutrons, threshold 11.3 MeV , $\sigma = 10$ mbarn
- $^{16}O(n,2n)^{15}O$ from fast neutrons, threshold 16.6 MeV
- $^{16}O(n,p)^{16}N$ from fast neutrons, threshold 10.2 MeV, con $\sigma = 40$ mbarn, possibile also from thermal neutrons $\sigma = 0.178$ mbarn
- $^{17}O(p,n)^{17}N$ (relative abundance of 17 Oxygen = 0.038 %)
- $^{40}Ar(n,a)^{37}S$ from fast neutrons, threshold 2.6 MeV, $\sigma = 10$ mbarn
- $^{40}Ar(n,p)^{40}Cl$ from fast neutrons, threshold 6.9 MeV , $\sigma = 16$ mbarn
- **$^{40}Ar(n,\gamma)^{41}Ar$ from thermal neutrons , $\sigma = 630$ mbarn**



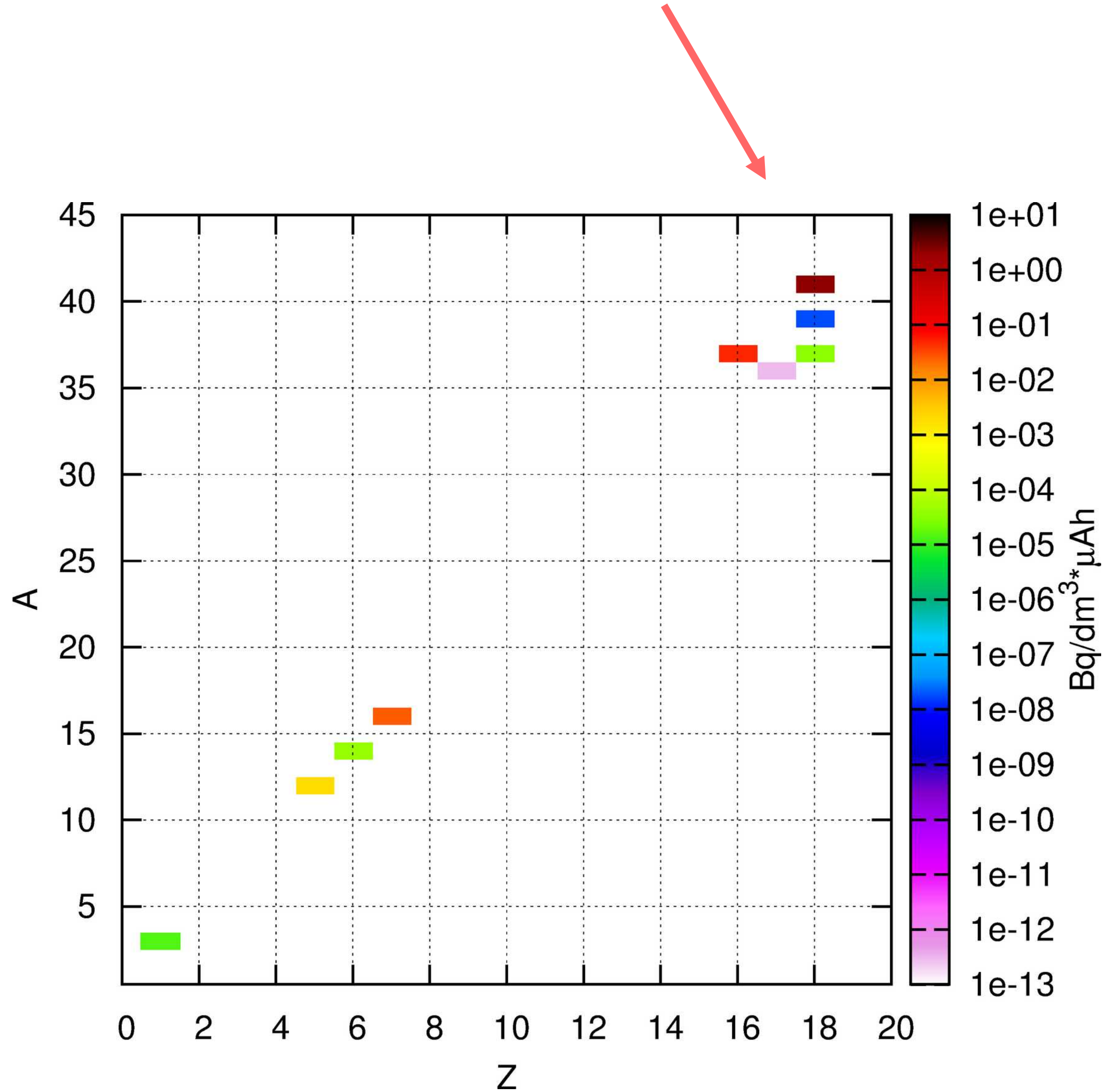

While analytical models (i.e. Birattari et al.) make possible an evaluation of the problem, again MC simualtions give accurate assessment of air activation taking into account the real geometry of air irradiation and neutron spectra

# Air activation



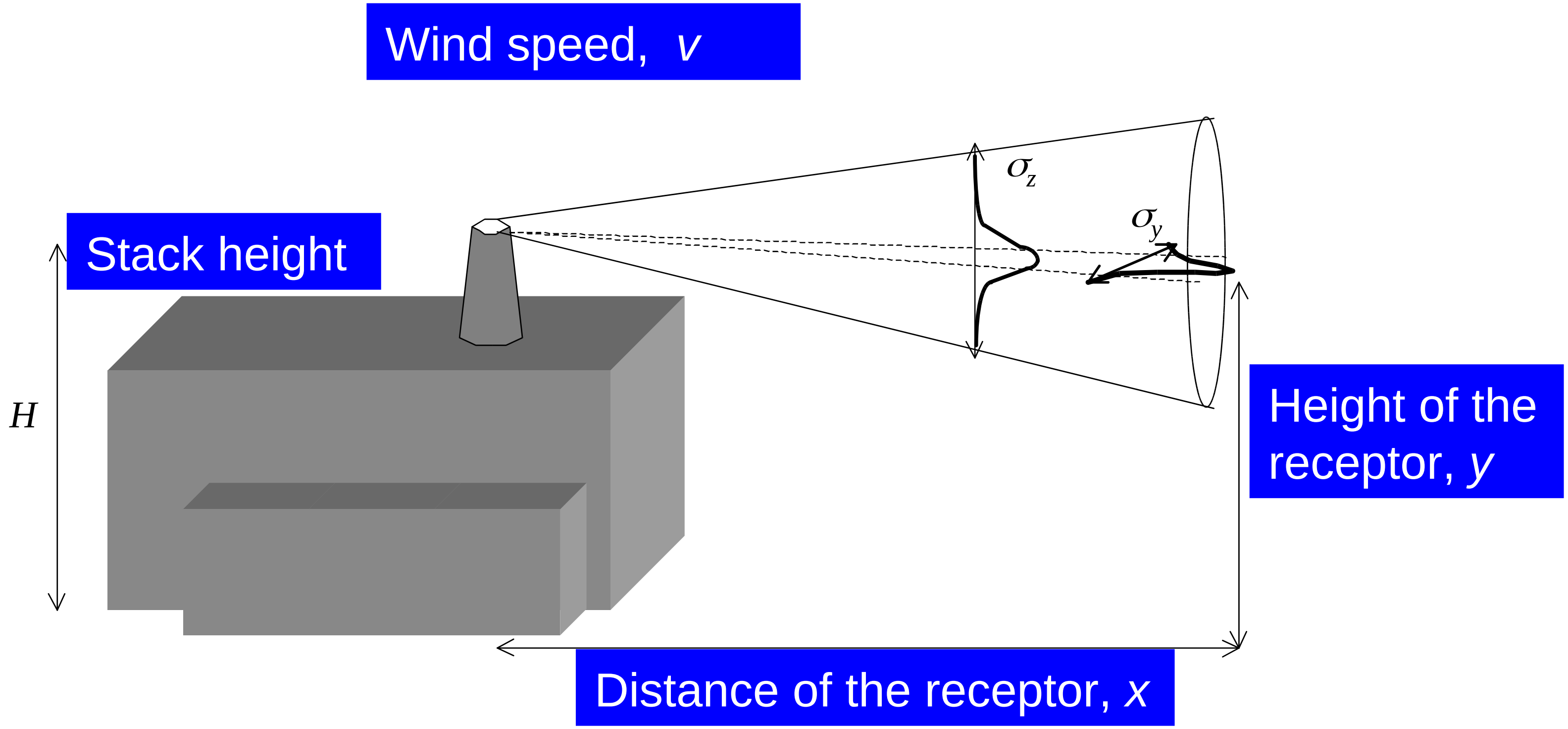
***Total volume***

| | |
|---|---|
| $C_{FLUKA}$ [Bq/dm³*µAh] | 2.18 ± 0.11 |
| $C_{exp}$ [Bq/dm³*µAh] | 0.86 ± 0.15 |
| $C_{FLUKA}/C_{exp}$ | **2.5 ± 0.5** |




*Cicoria et al. Modern Physics Letters A Vol. 32, No. 17 (2017) 1740014*

# Gaussian plume emission




$$C=\frac{Q}{2\pi\sigma_y\sigma_z\bar{u}}\exp\left\{-\frac{1}{2}\cdot\left[\frac{y}{2\sigma_y^2}+\frac{(z-h)^2}{2\sigma_z^2}\right]\right\}$$

(note: the distance *x* is implicitily involved in the calculation of $\sigma_y$ and $\sigma_z$)

# Design of safety systems

| Safety Intergity Level | 1 | 2 | 3 |
|---|---|---|---|
| Performance Requirements | | Safety Availability Range | |
| | 0.9 - 0.99 | 0.99 - 0.999 | 0.999 - 0.9999 |
| | | PFD Average Range | |
| | 0.1 - 0.01 | 0.01 - 0.001 | 0.001 - 0.0001 |

*Definitions from the Standard ISA-S84.01-1996 and IEC-61508*

All the components related to safety (microswitches, sensors, detectors,...) should be selected according to specifications taking into account their perfomance in terms of reliability and Probability of Fault on Demand (PFD)

# Design of safety systems

*Evaluation of fault probablility*

The probability of fault of a component is correlated to its mean time to fail (or mean time between failures):

$$MTBF = \frac{1}{\lambda_s}$$

$$PFD = R_s \cdot \lambda_s = \lambda_s \cdot e^{-\lambda_s \cdot t}$$

The evaluation of probability of fault depends on the component characteristics, type of installation and wiring, redundancy (single component, dual, in series, in parallel …)

# Examples of fault probability rates

*From  Merlin Gerin CT114 (apart Human error, evaluated)*

| Component | λ ($h^{-1}$) | PFD per 8000 h |
|---|---|---|
| Resistors | 1.00E-09 | 1.00E-09 |
| Microprocessors | 1.00E-06 | 9.92E-07 |
| Fuses | 1.00E-06 | 9.92E-07 |
| Breakers | 1.00E-06 | 9.92E-07 |
| Relais | 1.00E-06 | 9.92E-07 |
| Power supply | 1.00E-05 | 9.23E-06 |
| Sensors | 1.00E-04 | 4.49E-05 |
| Photocells | 1.00E-04 | 4.49E-05 |
| Lamps | - | 5.00E-02 |
| Human error | - | 5.00E-02 |

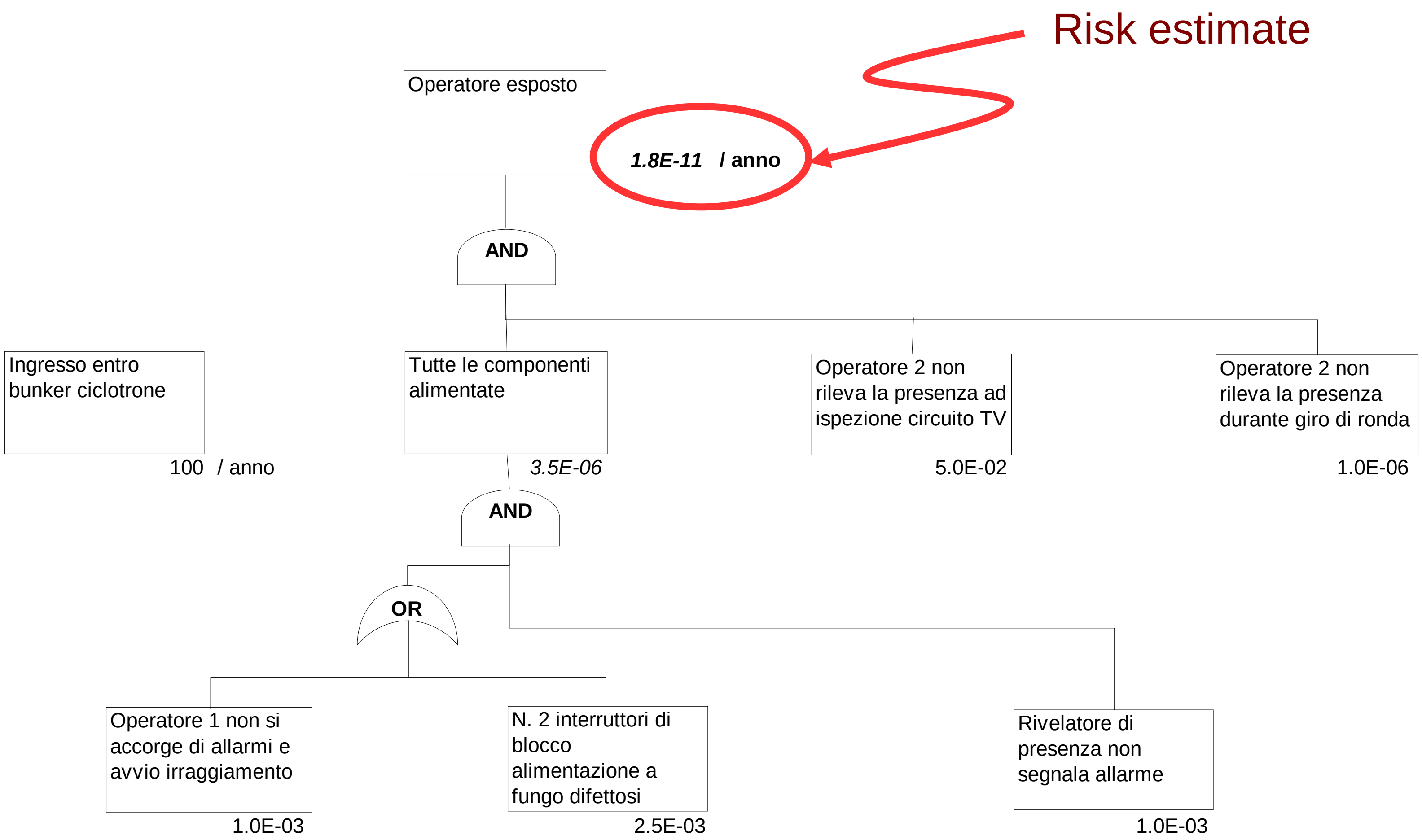
# Hazop analysis of risks

## Analisi rischi operativi - Hazop

caso di intrappolamento inavvertito di un operatore ed avvio irraggiamento

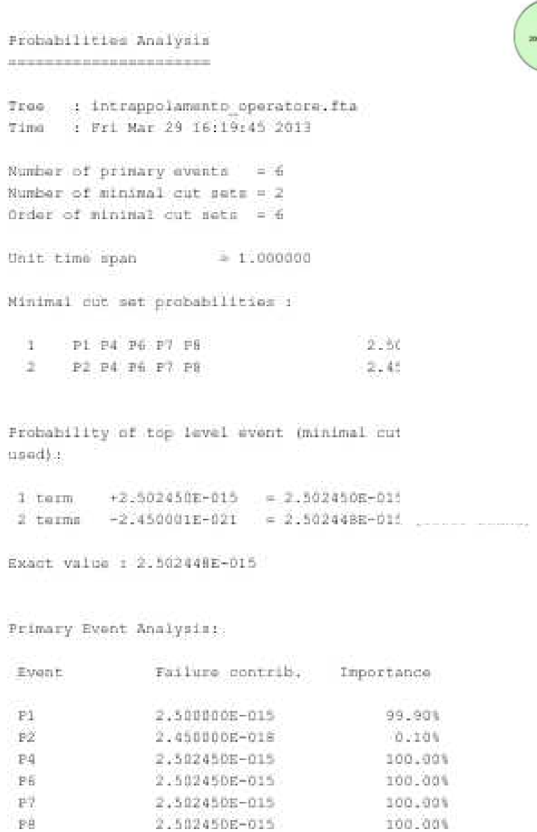
*Probabilità di base adottate:*

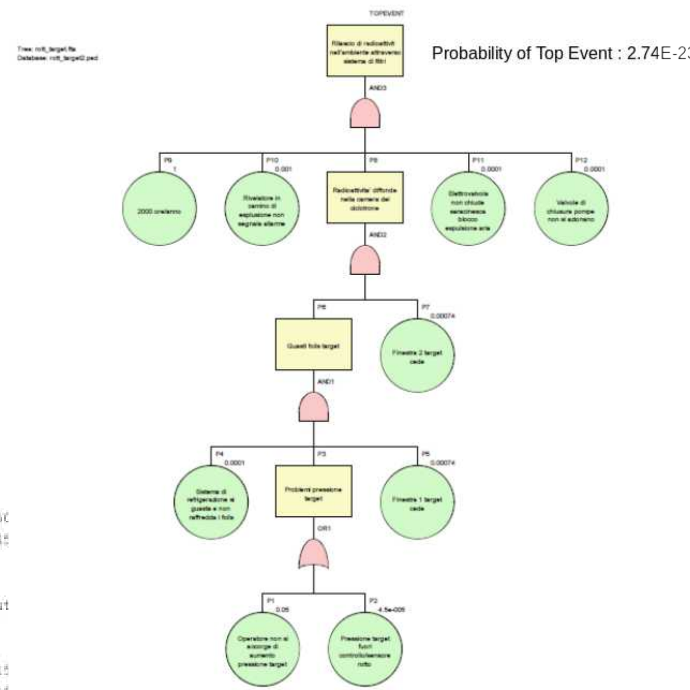
| | |
|---|---|
| sistema elettrico o meccanico semplice | 5.0E-02 per operazione |
| sistema informatizzato o complesso | 1.0E-03 per operazione |



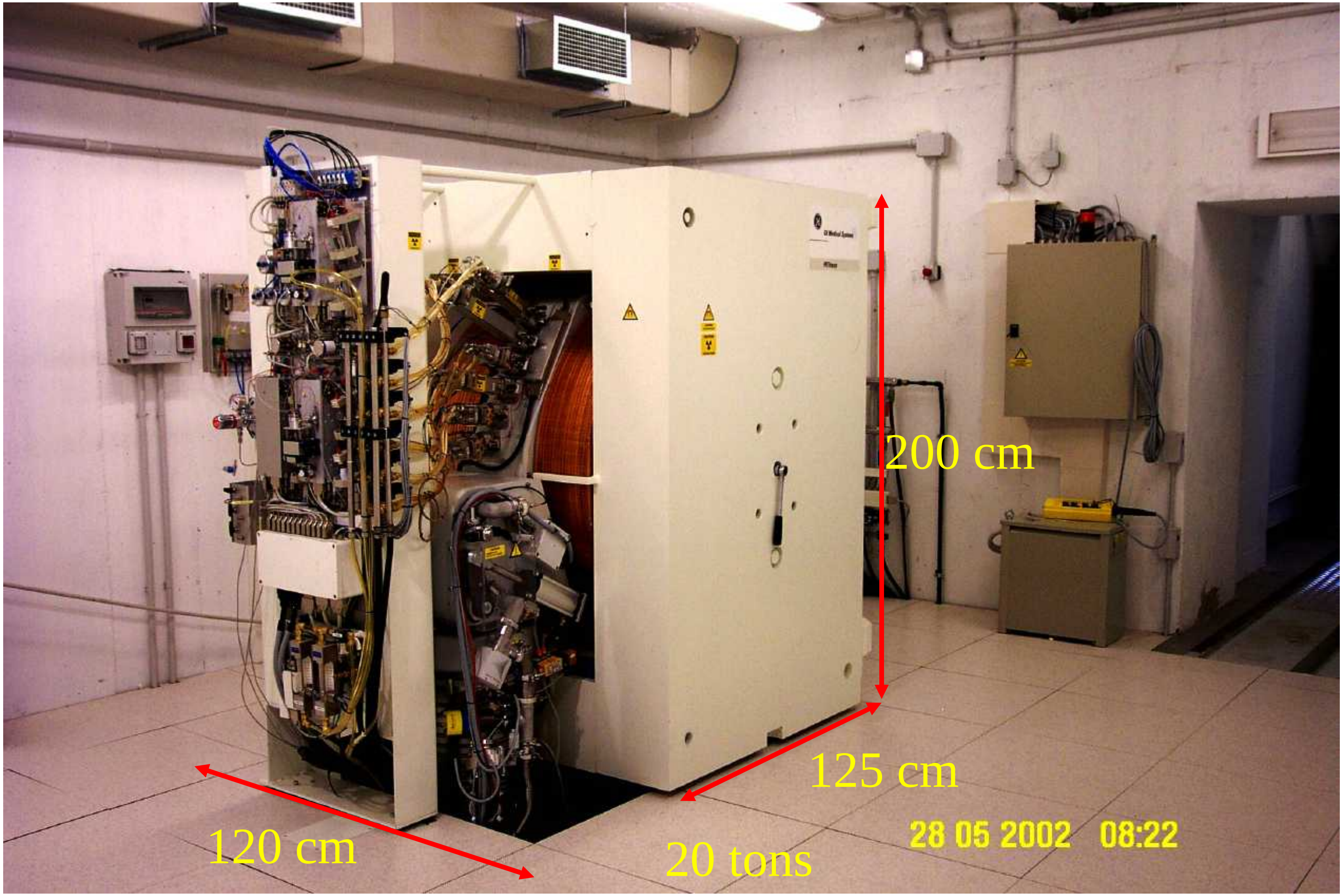
# Modern tools for fault tree / Hazop analysis

- Modern software tools, like Isograph or OpenPHA, help nowadayr to easy perfomr Hazop analysys
- Typically, these softwares include librariers of “default” MTBF or fault rates for generic components
- A detailed statistical analysys of each case is perfomed in minutes


```
Probabilities Analysis
======================

Tree    : intrappolamento_operatore.fta
Time    : Fri Mar 29 16:19:45 2013

Number of primary events   = 6
Number of minimal cut sets = 2
Order of minimal cut sets  = 6

Unit time span          = 1.000000

Minimal cut set probabilities :

  1     P1 P4 P6 P7 P8                    2.5(
  2     P2 P4 P6 P7 P8                    2.4!


Probability of top level event (minimal cut
used):

 1 term    +2.502450E-015    = 2.502450E-015
 2 terms   -2.450001E-021    = 2.502448E-015

Exact value : 2.502448E-015


Primary Event Analysis:

 Event          Failure contrib.    Importance

 P1             2.500000E-015           99.90%
 P2             2.450000E-018            0.10%
 P4             2.502450E-015          100.00%
 P6             2.502450E-015          100.00%
 P7             2.502450E-015          100.00%
 P8             2.502450E-015          100.00%
```



# Homer



# Protection against electrical shocks

Safety pushbottons

Toxic gases detector

# Safety systems for plug door motion

impact
detectors

glass door for access
restriction

photocells

# Inspection rounds

Temporal sequence
of pushbottons

First approach to limit the risk of operator entrapment inside the bunker

# TV control

Shielding, to protect the CCD detector

mirror, for indirect vision

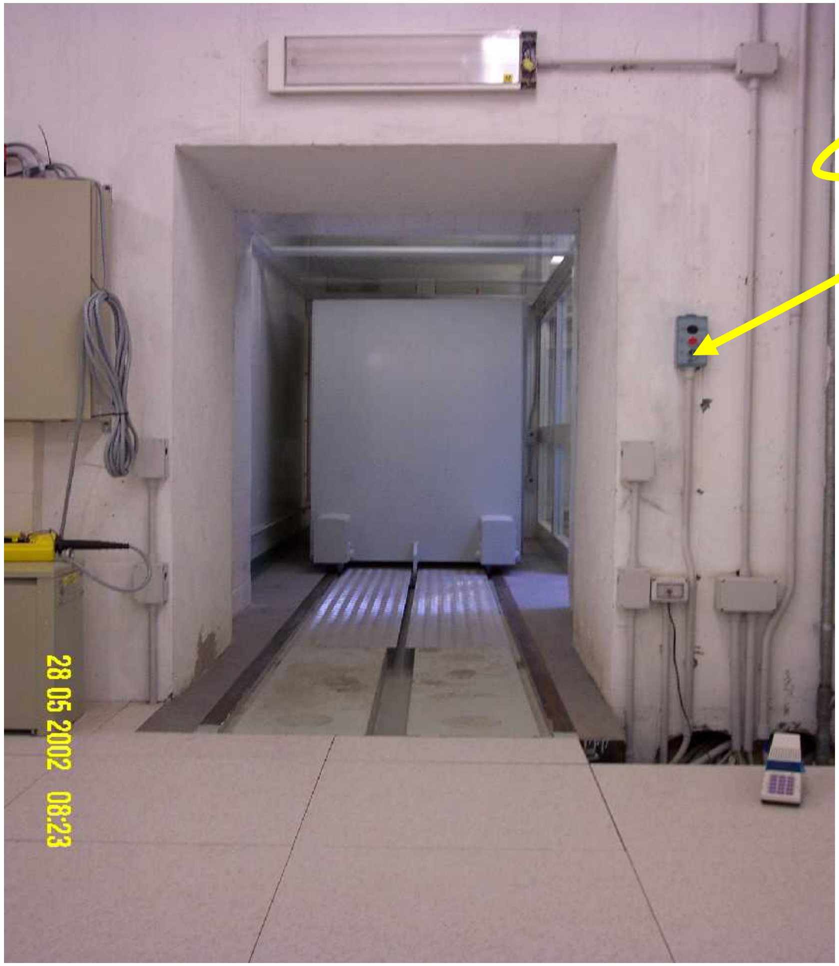
Second approach to limit the risk of operator entrapment inside the bunker

# Escape way from the bunker

Pushbotton to open the plug door from inside the bunker

- single push action
- opening request prioritary on closing request
- doors open in the direction of the escape way

# Escape way from the bunker




Pushbotton to open the plug door from inside the bunker

- single push action
- opening request prioritary on closing request
- doors open in the direction of the escape way

An operator should NEVER be inside the bunker with the plug door closed !

# Visual and acoustic signals

plug door motion

Beam ON

Radiofrequecy ON

Magnet ON

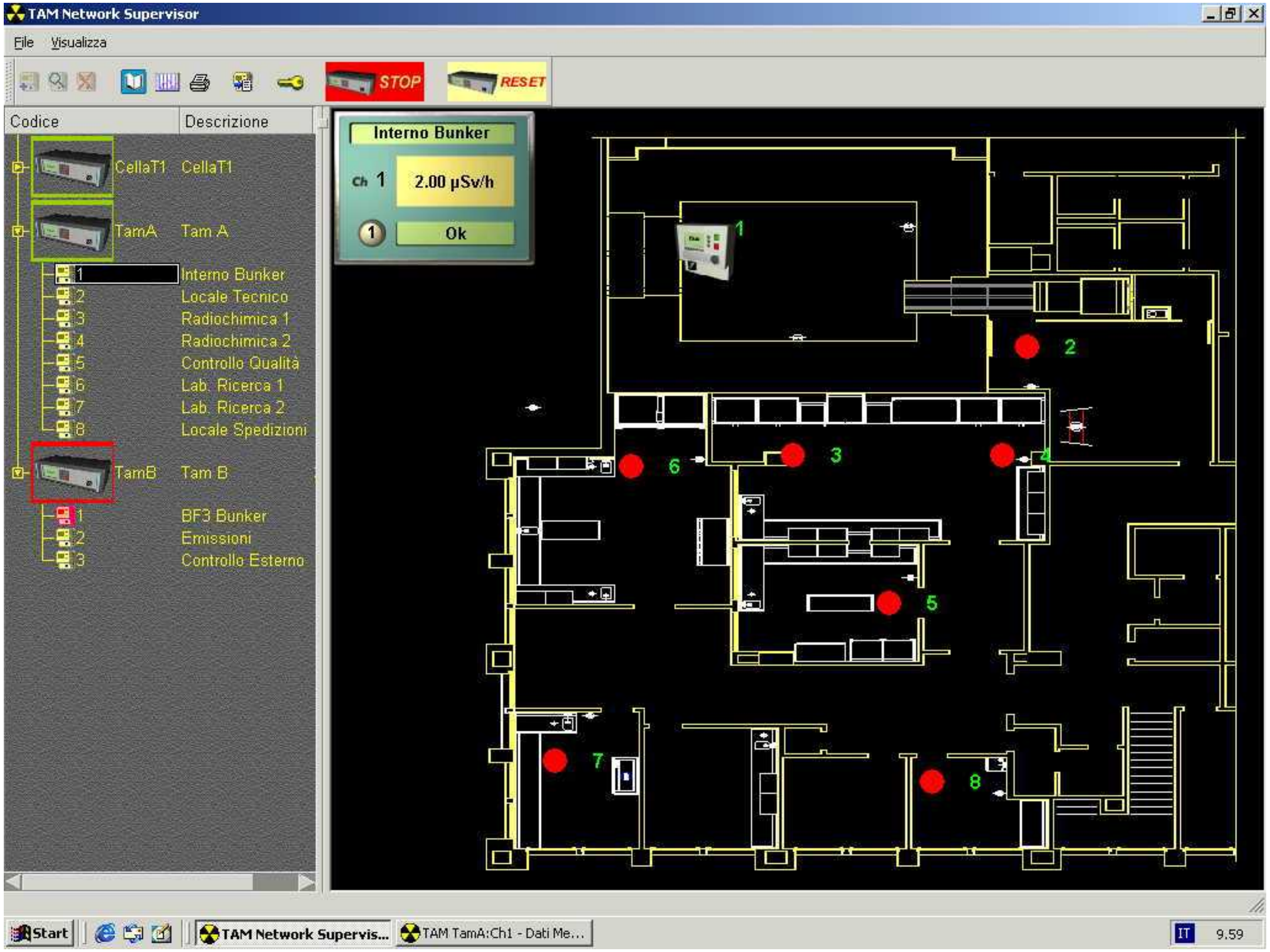
Green light "OK"

# Motion detection system

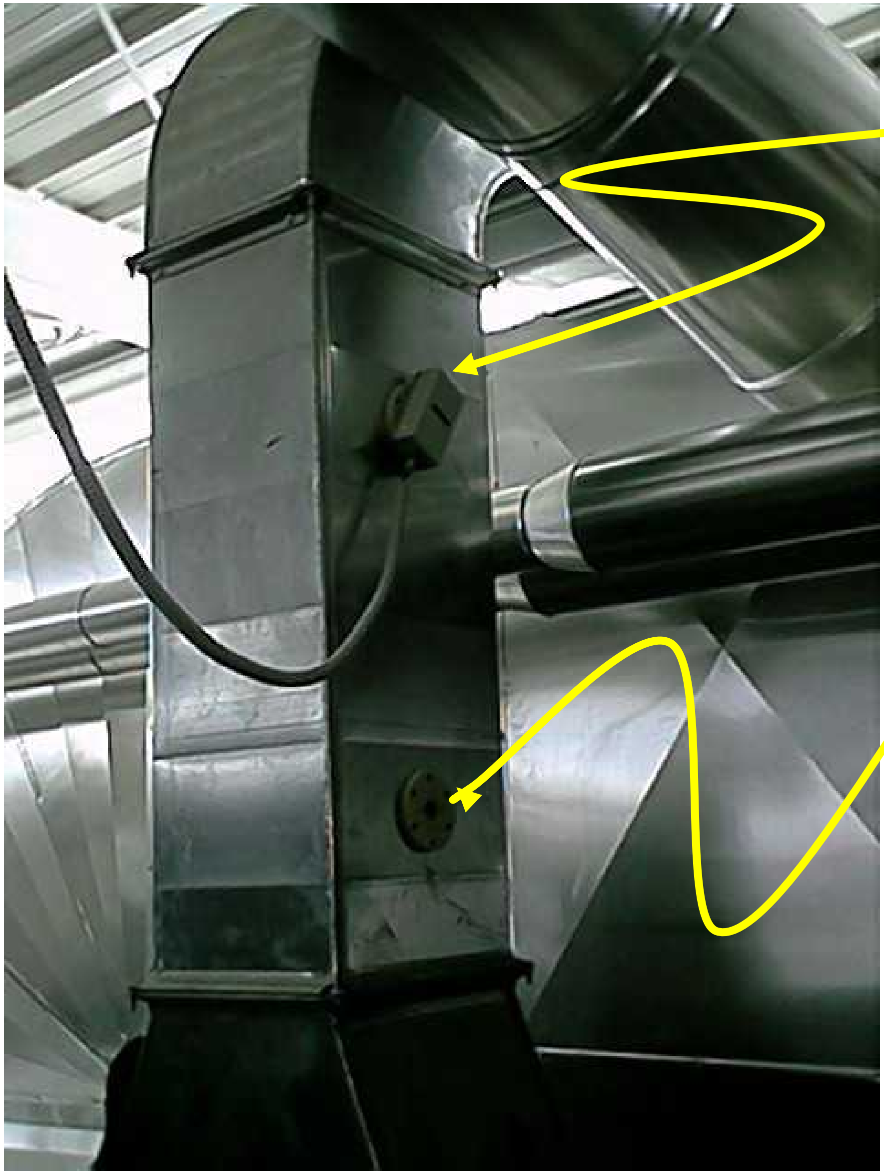

Third approach to limit the risk of operator entrapment inside the bunker

# Radiation monitoring system

## interlock to access in specific areas



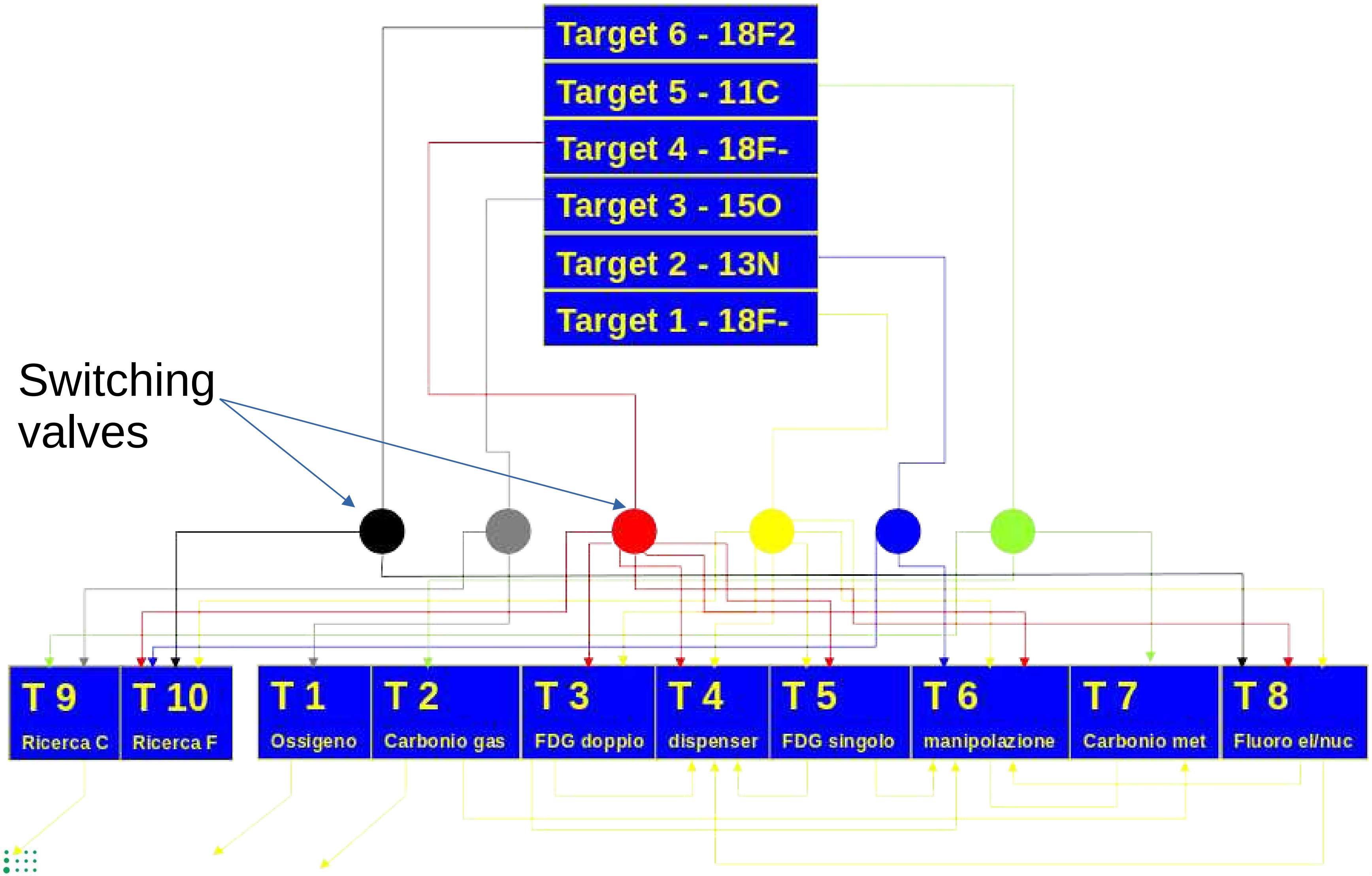
# Air exhaust emissions control



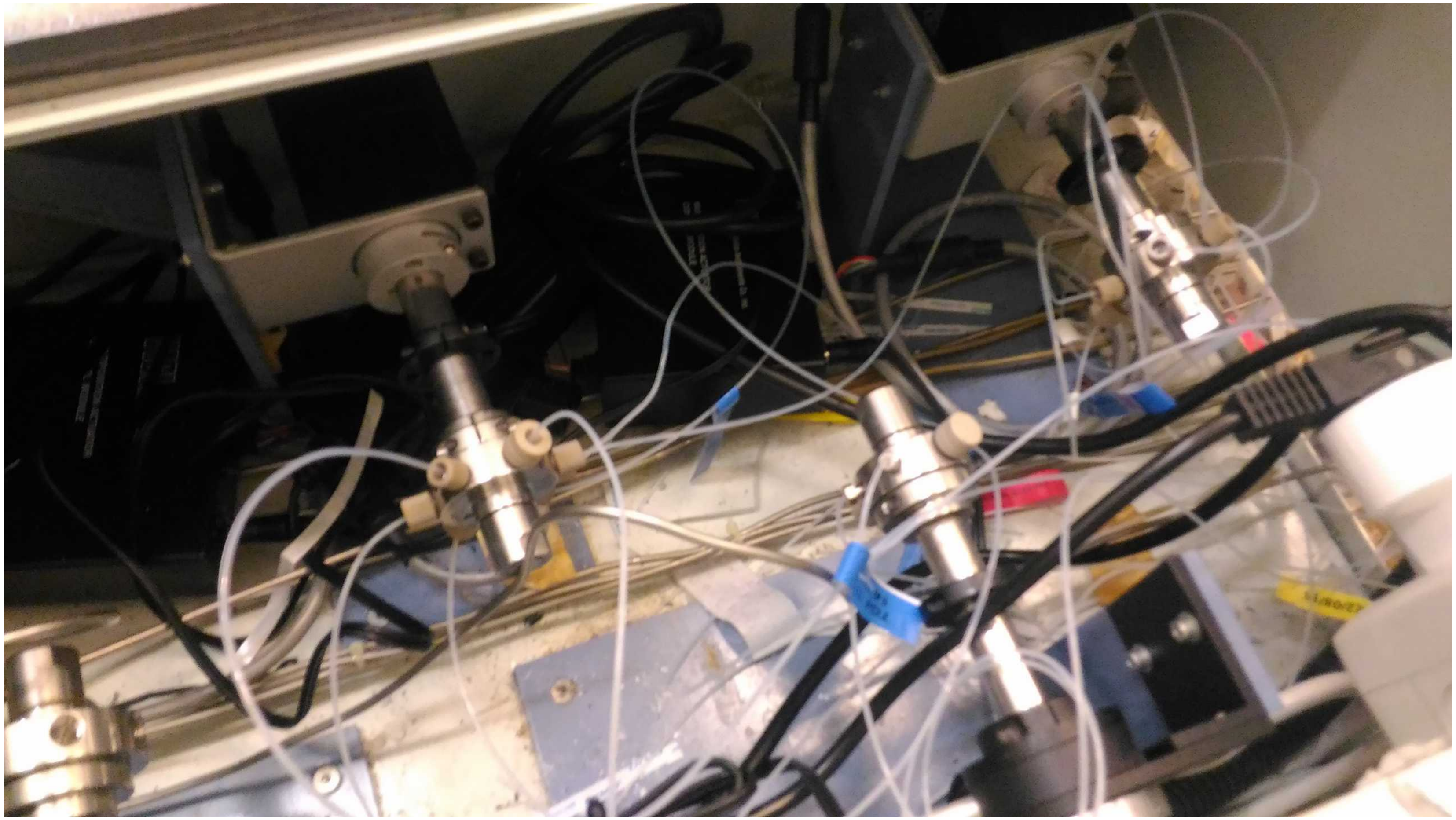
Detector positioned on the emission stack

Flange for calibration source positioning

# Lines and valves for activity delivery



# Switching valves for activity delivery in Bologna

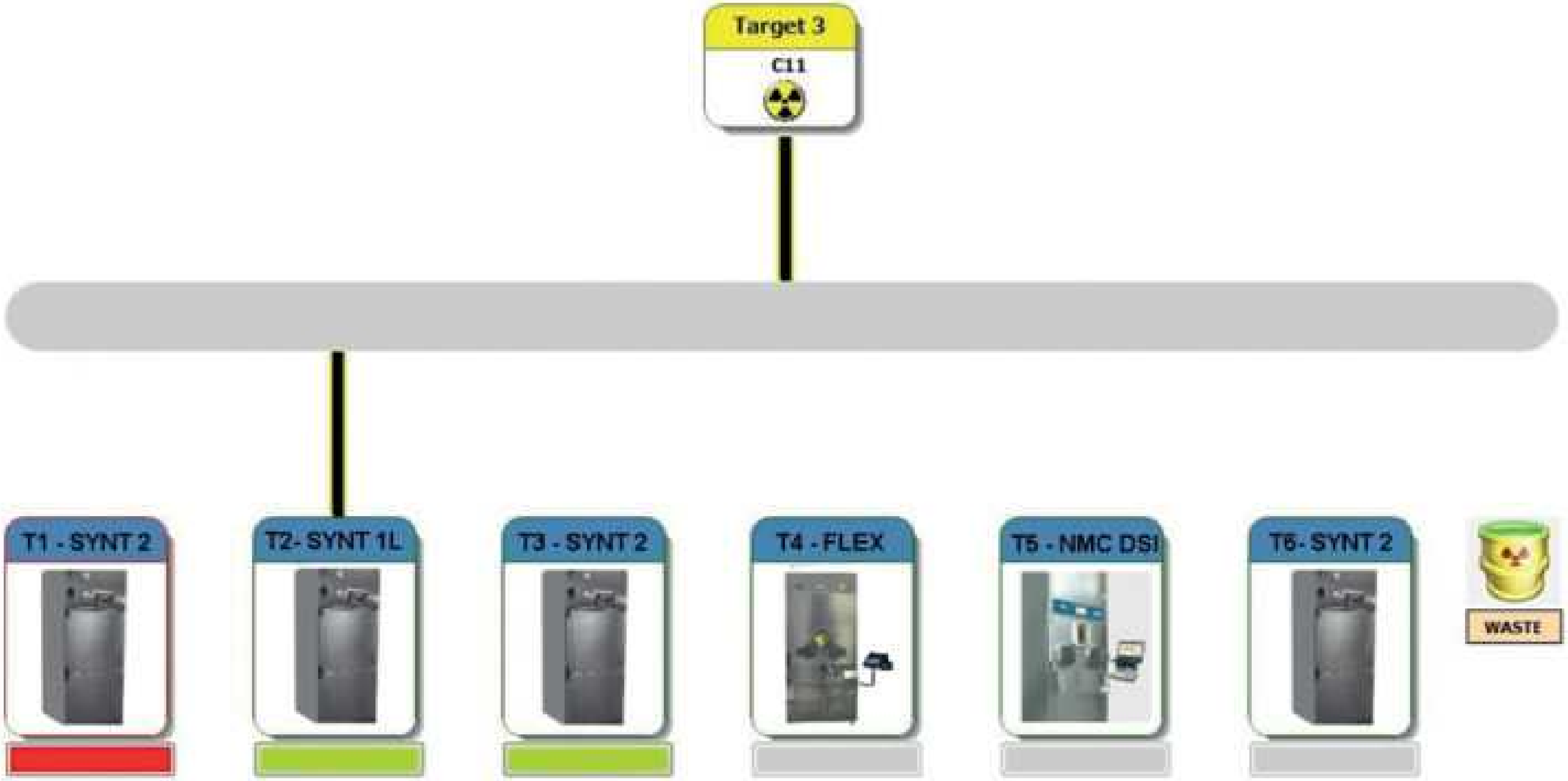


*This prototype solution has been improved and marketed by TEMASinergie*

# Lines and valves for activity delivery


A system of automatic valves, Ethernet controlled by dedicated software, that makes it possible to decide, for each target of the cyclotron, which cell the radioactive bolus will be sorted into:

- avoiding manual switching operations and therefore minimizing the time between one irradiation and the next;
- performing a check on the destination cell via Ethernet and allowing delivery only if the required safety conditions are met.

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- performing a check on the destination cell via Ethernet and allowing delivery only if the required safety conditions are met.

# Safety system connection box

Hardware check on functionality of the safety systems

# Access to cyclotron bunker

- Operators accessing the bunker should know well the tasks they are going to perform
- Check the level of dose inside the bunker prior to enter
- Check their personal dosimeters  prior to entrance
- In the case the magnet is ON leave their credit cards, watch, mobile phone, etc.
- Carry on a portable instrument to verify the level of dose in the working positions
- Stay only in correct positions, avoiding permanence near the targets
- Performing the necessary operations as quickly as possible

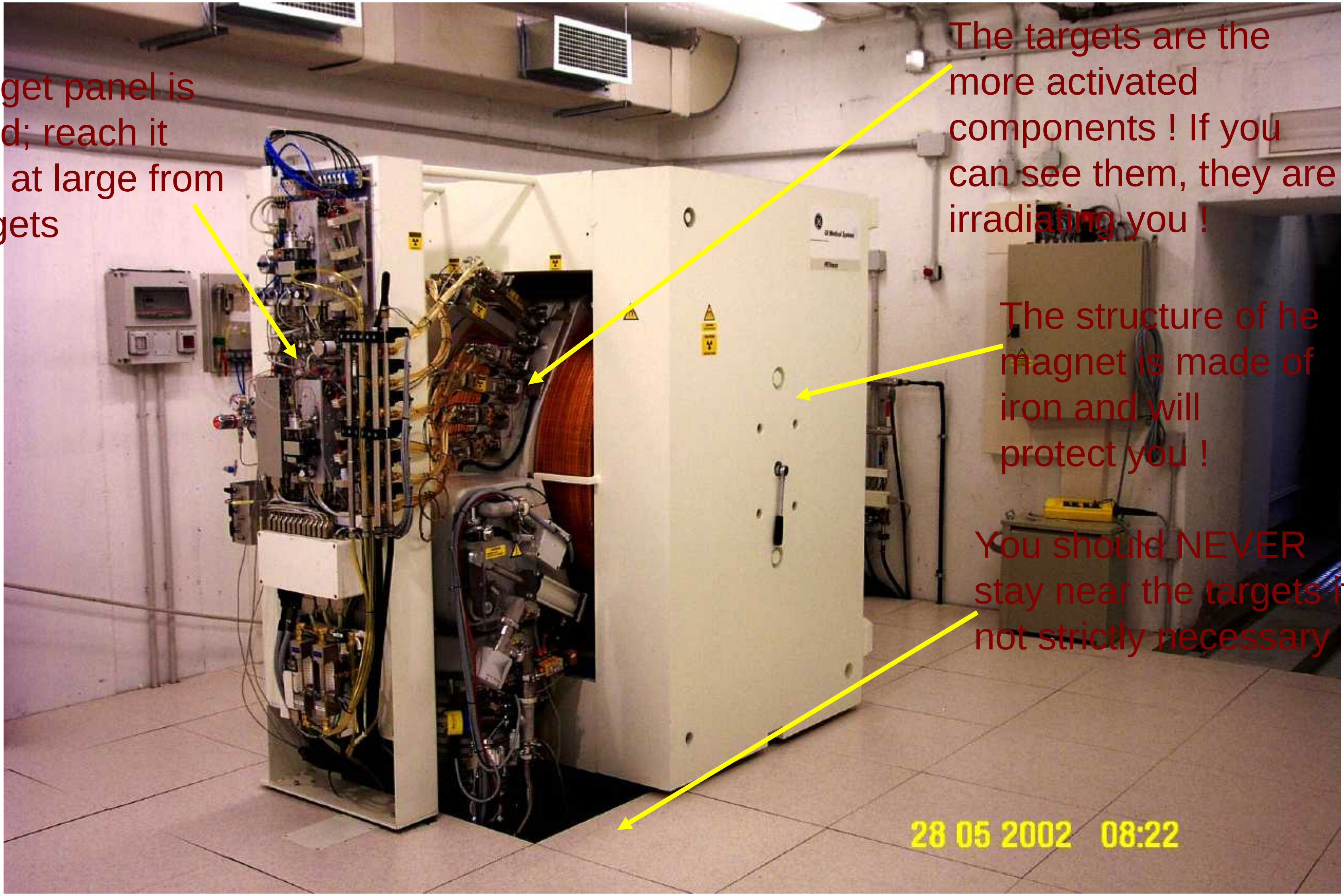
# Inside the bunker

The target panel is shielded; reach it staying at large from the targets

The targets are the more activated components ! If you can see them, they are irradiating you !

The structure of he magnet is made of iron and will protect you !

You should NEVER stay near the targets if not strictly necessary !



# Inside the bunker

About 1 hour after the last bombardment :

- the dosimeter installed on the wall will measure about 25 μSv/hour
- near the target panel the dose rate will be about 125 μSv/hour
- in the proximity of the magnet the dose rate will be approximately 25 μSv/hour
- at 100 cm from the targets > 300 μSv/hour !!!

According to the Internal Rules access to the bunker is possible only after a waiting time (in Bologna, 6 hours after the last bombardment).

In the case of urgent need to enter the bunker, ask confirm of the possibility of access to the Radiation Protection Officer.

# Ordinary maintenance

6 $^{18}F_2$-target

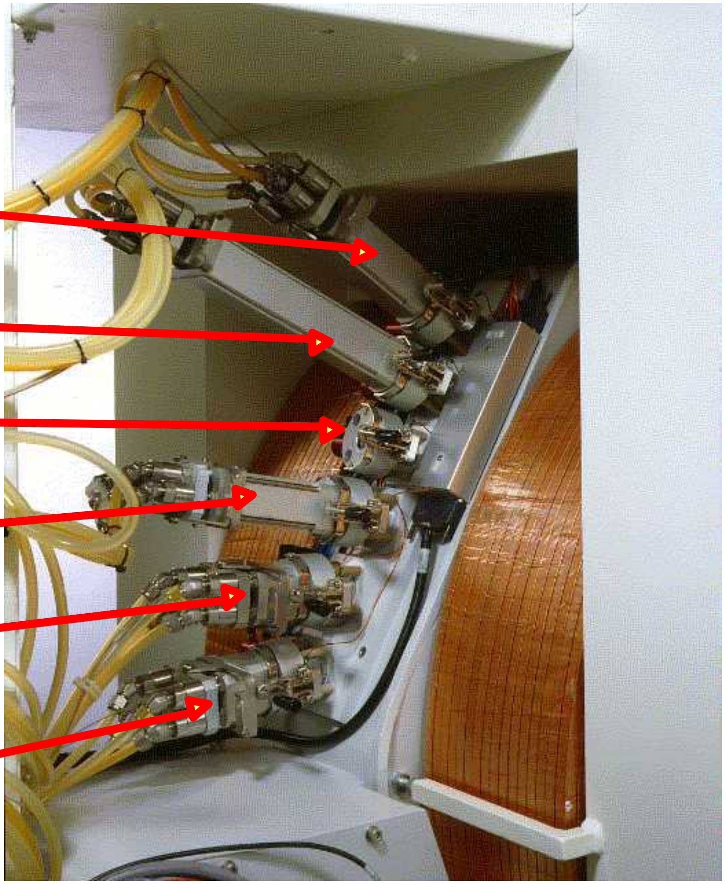
5 $^{11}C$-target

4 $^{18}F$-target

3 $^{15}O$-target

2 $^{13}N$-target

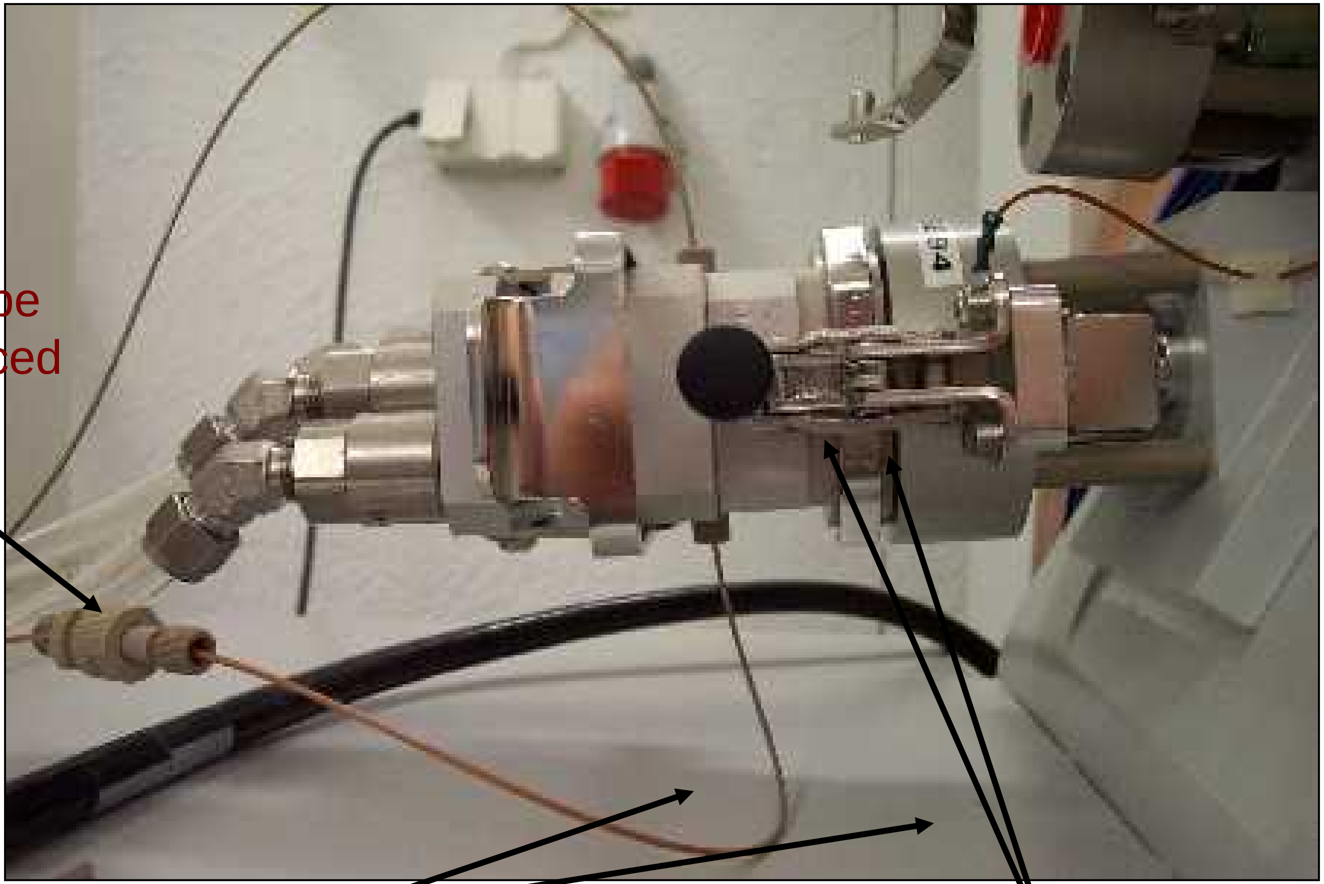
1 $^{18}F^-$-target



Frequently, maintenance operations involve targets. Learn and remember their identity and positions.

# Ordinary maintenance

## Target for $^{18}F^{-}$ production

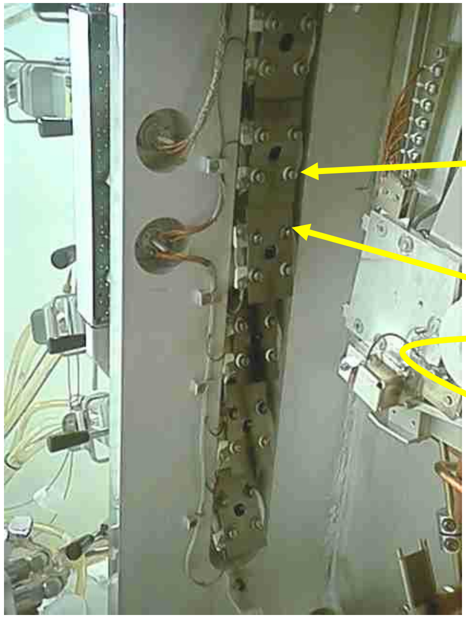


This filter should be periodically replaced

If you have to work near the target, you can add a partial shielding by placing some leas bricks on this plate.

The most activated components are the target foils, that are in the front part of the target.

# Preventive maintenance



Apart the targets, the most activated components are the collimators and the extraction foils.

In the case it is necessary to open the cyclotron vacuum chamber:

- plan the work in advance
- wear working clothes
- always use gloves
- always wear a protective mask
- always use plastic goggles
- … and please, do not forget any tool inside the chamber …

# Incidents related with acces to the bunker

The cases of:

- Operator “trapped” in the bunker
- Irradiation start while the bunker door is open
- Opening of the bunker door during irradiation

Door microswitches,
Light and sound alarms,
power off pushbottons,
saftey trip pushbottons,
TV cameras, motion detection

Are all managed by engineered saftey system installed as components of bunker safety; if these systems are normally maintened, and if the are NOT DELIBERATELY BY-PASSED, the probabilties of operator irradiation due to fault in the systems, have been calculated in the range $10^{-11}$ – $10^{-25}$ per year, depending on the achitecture of the safety system.

In conclusion, currently adopetd saftey systems are normally sufficient to reduce the risk of these exposure scenarios to a negligible level of likelihood.

## Target rupture:
## A frequently asked scenario, that is actually a fake incident

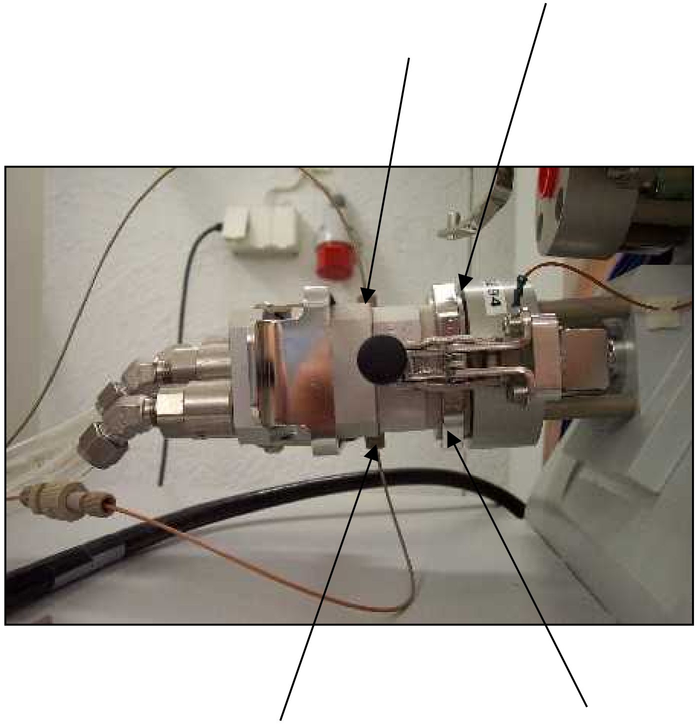
This one of the most asked scenarios ... but actually all the worries come from a lack of knowledge on how cyclotrons are made and operate:

- Targets are fitted on the vacuum chamber; if both target foils broken, the activity in the target is sucked by the vacuum.
- The vacum is granted by a sequence of diffusion (or criogenic) pumps and mechanical pumps. Once a target brokens, the fast pressure increase in the acceleration chamber, activate safety valves immediately to insulate the chamber, to protect the diffusion (crio) pumps.
- In the case the very first “puff” of radioactivity reaches the pumps, it is trapped ! (pumps are there for this reason ! And they do very well !!!).
- Activity is typically distributes on the walls of the acceleration chamber. A waiting time of a few hours is sufficent to grant sufficein reduction in the activity level, to open and clean the chamber.

Simply, this is not a real incident scenario.

# What can really happen ...

- Each target has several fittings, for the IN/OUT connections of target material
- The front flange and the Helium cooling system for the fornt part of the target may loose tightness
- A valve in the line of target filling / emptying may leak



In these cases,during the irradiation, or during the delivery of the activity produced, there may be a leak. This release of activity may contaminate the air inside the bunker and be potentially released:

- Targets are normally thigt checked (for a short time) before each irradiation
- The prabability evalauted forthis type of inciend is of the order of ~ $10^{-5}$ or less
- Air exhausted is typically filtered and checked for activity before release

These aspects minimize risk for the environnment.

# Monitoring of internal contamination. Decision Factor

***(IAEA-Safety Guide no. RS-G-1.2)***

- The whole maintenance programme has to be divided into main operations from the radiation protection point of view
- Estimation of the Activity handled using the work load data of General Electric for own workers
- Estimation of the Safety Factors suggested by IAEA
- Calculation of the Decision Factor D given by:

$$D=\frac{\sum_{j=1}^{P}\sum_{i=1}^{N} A_{i,j}[Bq]\,e(g)_{i,inh}\left[\frac{Sv}{Bq\cdot y}\right] f_{fs} f_{hs} f_{ps}}{0.001\left[\frac{Sv}{mSv}\right]}$$

$>1$ → NEED FOR INDIVIDUAL MONITORING

$<1$ → NO STRICT NECESSITY OF INDIVIDUAL MONITORING

# Summary of relevant radionuclides

| Radionuclide | Half-life(d) | Reaction |
|---|---|---|
| $^{51}Cr$ | 27,70 | $^{54}Fe(n,\alpha)^{51}Cr$ |
| | | $^{52}Cr(n,2n)^{51}Cr$ |
| $^{52}Mn$ | 5,591 | $^{52}Cr(p,n)^{52}Mn$ |
| $^{54}Mn$ | 312,3 | $^{54}Cr(p,n)^{54}Mn$ |
| | | $^{54}Fe(p,n)^{54}Mn$ |
| | | $^{55}Mn(n,2n)^{54}Mn$ |
| $^{55}Co$ | 0,729 | $^{58}Ni(p,\alpha)^{55}Co$ |
| $^{56}Co$ | 77,27 | $^{56}Fe(p,n)^{56}Co$ |
| $^{57}Co$ | 271,79 | $^{57}Fe(p,n)^{57}Co$ |
| | | $^{60}Ni(p,\alpha)^{57}Co$ |
| $^{58}Co$ | 70,82 | $^{58}Fe(p,n)^{58}Co$ |
| | | $^{58}Ni(n,p)^{58}Co$ |
| $^{65}Zn$ | 244,26 | $^{65}Cu(p,n)^{65}Zn$ |
| $^{181}W$ | 121,2 | $^{181}Ta(p,n)^{181}W$ |
| $^{182}Ta$ | 114,43 | $^{181}Ta(n,\gamma)^{182}Ta$ |

# Assessment of activity manipulated and of safety factors

| | |
|---|---|
| Manipulated activity | Estimated using maintenance company and Hospital workers workload data |
| Dose coefficients | ICRP Publication 68 |
| Safety factors | IAEA Guidelines |

CALCULATION OF THE DECISION FACTOR

Hospital Physicists: → 0.21

Company field engineers: → 0.84

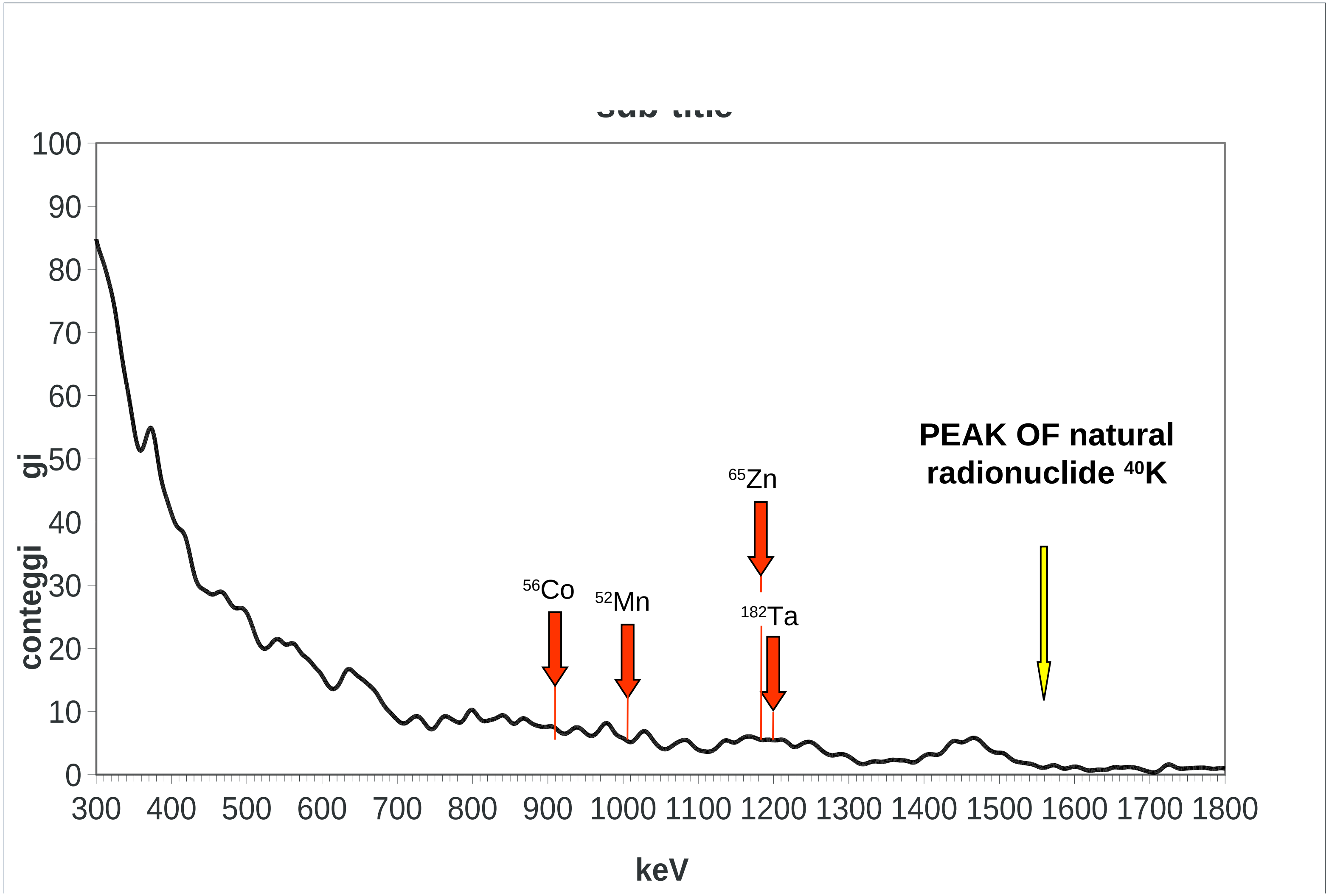
*Terranova et al., Radiat Prot Dosimetry. 2010 Nov 3*

# Simplified geometry of whole body counting


Measuring time: 300 s

*Terranova et al., Radiat Prot Dosimetry. 2010 Nov 3*

# Example of in-vivo measurement




Minumum Detectable Activity ~ 1000 Bq

# Maintenance operations

- always wear protective clothes (apron, other working clothes)
- check that you have your personal dosimeters
- always wear protective gloves
- always wear a nose mask and plastic goggles
- bring with you a portable dosimeter
- prepare in advance all the tools needed
- if necessary, use lead bricks to add shielding
- … and always remember time and distance factors

- plan your work in advance
- do not try to do by yourself tasks that need two people
- in the case of anomalous findings or risk of irradiation

**FIRST OF ALL GO AWAY,**
**RECONSIDER THE SITUATION AND THINK WHAT TO DO**
**ASK ADVICE AND ACT ONLY WHEN YOU ARE SURE !**

# Conclusions - I

- Cyclotrons are well known radiation sources; the needs for their safe installation are fairly well documented and there is a current good practice of engineered safety systems
- the cyclotron is a source of radiation both during and after a bombardment
- access to cyclotron bunker is subject to restrictions
- the shielded door of a bunker may be very heavy; safety systems are needed to avoid the risk of injury during its motion
- metallic components inside the bunker are usually activated; in particular, the targets will be highly activated
- some components inside the vacuum chamber of the cyclotron may be source of contamination (powders, oils, fragments of stripping foils …); always wear protective clothes, gloves and face mask when servicing the cyclotron
- at short distances, beta radiation may contribute significantly to the absorbed dose
- the cyclotron and its subsystems can be sources of magnetic fields, electromagnetic fields, electrical shocks. Always pay attention to cartels, signs and light indicators

# Conclusions - II

- HAZOP and fault tree analysis codes may help in planning safe installations and evaluate the residual probability of incident scenarios
- The risk of operator’s entrapment in the bunker should be eliminated (reduced to transcurable levels, e.g. < $1E^{-10}$ /year)
- The scenario of target rupture is overlookd; it is not a real incident condition
- Unplanned releases are possible due to leakage in a variety of componets (targets, valves, delivery lines). All of these should be regularly checked for tightness.
- In the (unlikley) case of unplanned relesaes, given the physical characteristics of the radionuclides of interest, the environmental impact and consequences for the general public are expected to be very limited (if any).