Elettra Sincrotrone Trieste

# Synchrotron facilities radiation safety issues


Katia Casarin

katia.casarin@elettra.eu

# Summary

- ✓ Sources of ionizing radiation at synchrotron facilities
- ✓ Shielding design
- ✓ Personnel Safety Systems
- ✓ Radiation monitoring
- ✓ Area and worker classification
- ✓ Training

# Ionizing radiation sources at synchrotron facilities

**Prompt radiation fields**

It include all radiation fields that disappear immediately when the accelerator is switched off.

- ✓ **Electrons**
- ✓ **Photons**
- ✓ **Neutrons**
- ✓ **Muons**

**Induced radioactivity**

It includes all radiation emitted by the radionuclide produced inside accelerator components.

It is present also when the accelerator is switched off.

- ✓ **Different types of radiation emitted in the nuclear decay.**

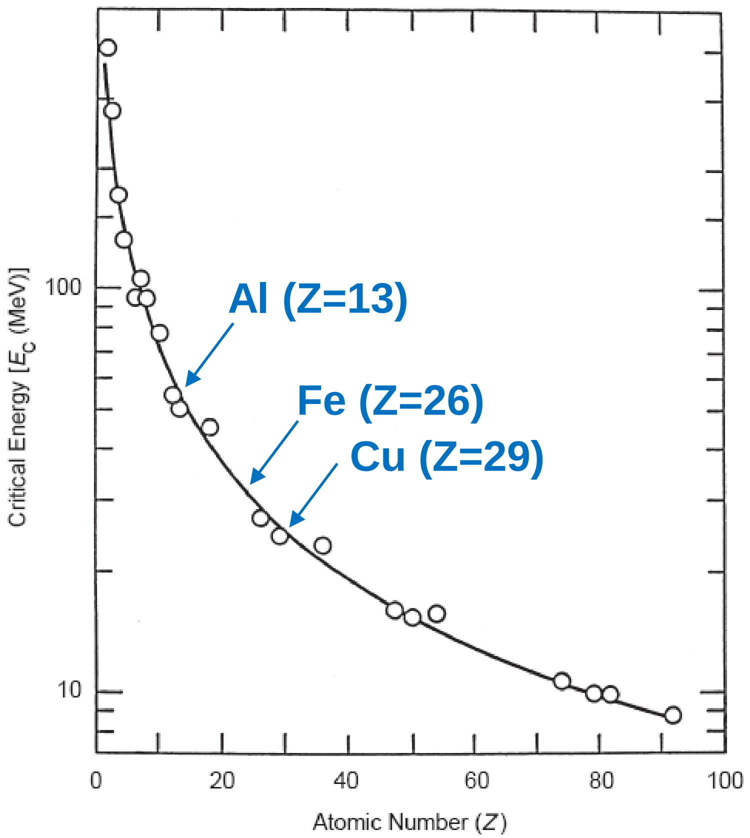
Elettra Sincrotrone Trieste

# Electrons

- ✓ At synchrotron facilities high energy electron beams are stored to produce synchrotron radiation.
- ✓ In general the interaction of the electron beam with the accelerator components or with the residual gas of the vacuum chamber produces beam losses.
- ✓ The critical energy $E_c$ defines the boundary where electron collision losses equal radiation losses:

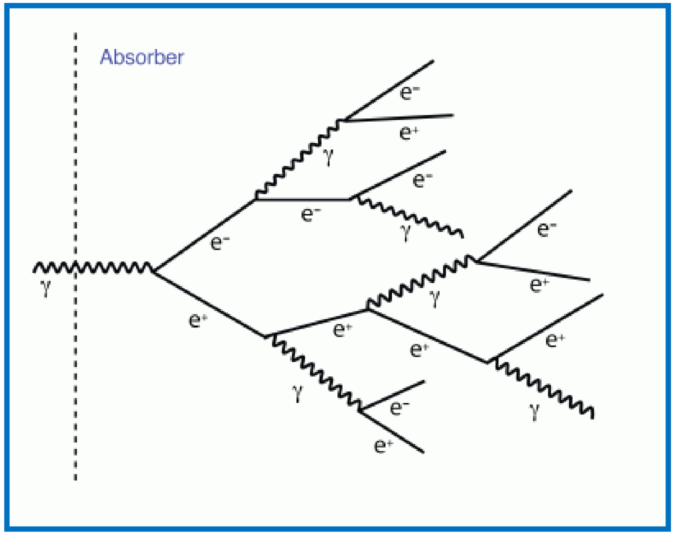
$$E_c(MeV) = \frac{800}{Z + 1.2}$$

- ✓ High energy electrons hitting materials will lose energy almost exclusively by generating photons (the so called bremsstrahlung radiation).



# Development of the electromagnetic (EM) shower

- ✓ Photons will produce electron-positron pairs and both the electrons and the positrons will generate further photons: this multiplication process (EM shower) will continue until energy falls below $E_c$.



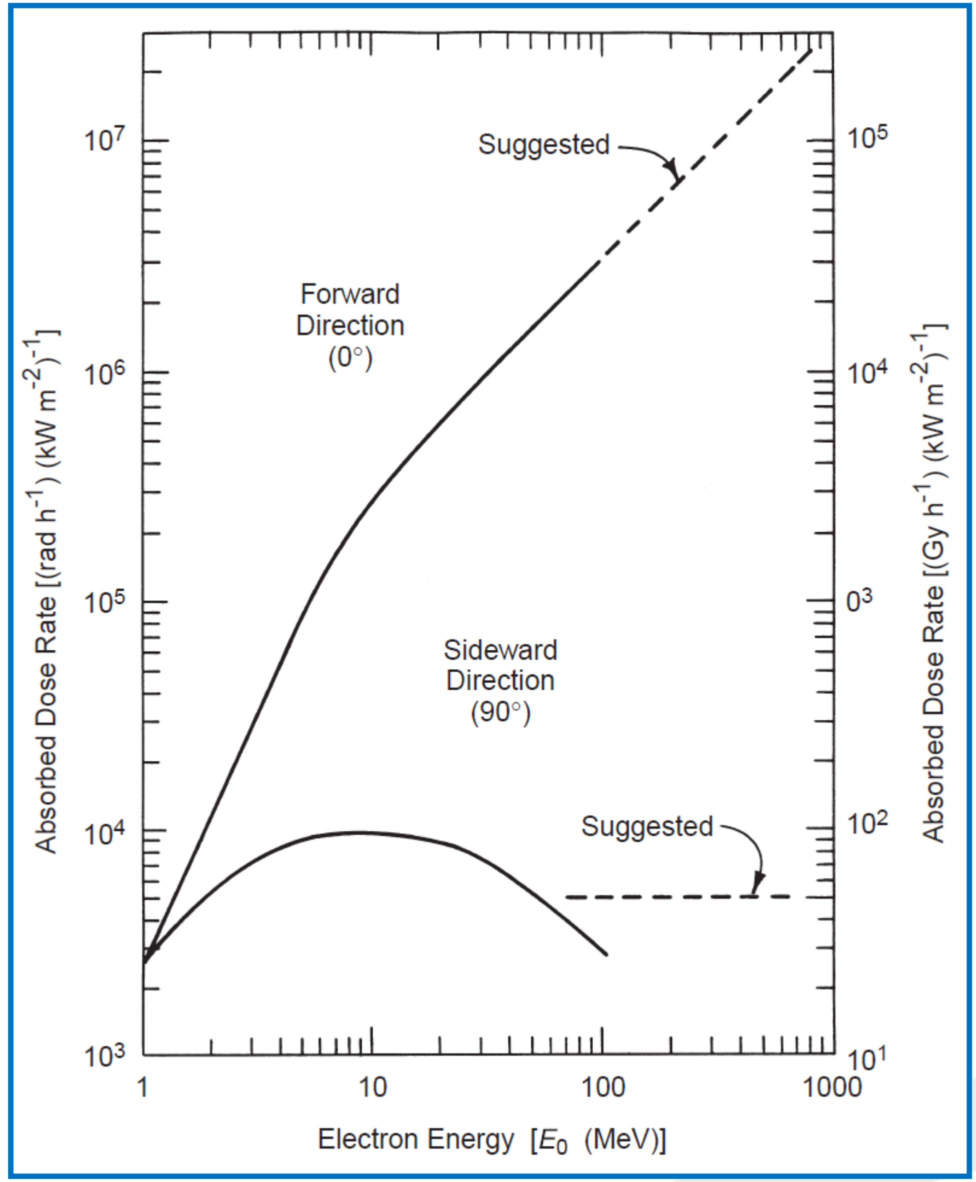

**Development of the EM shower.**

- ✓ Below $E_c$, the number of particles in the EM shower will start decreasing.

Elettra Sincrotrone Trieste

# Bremsstrahlung

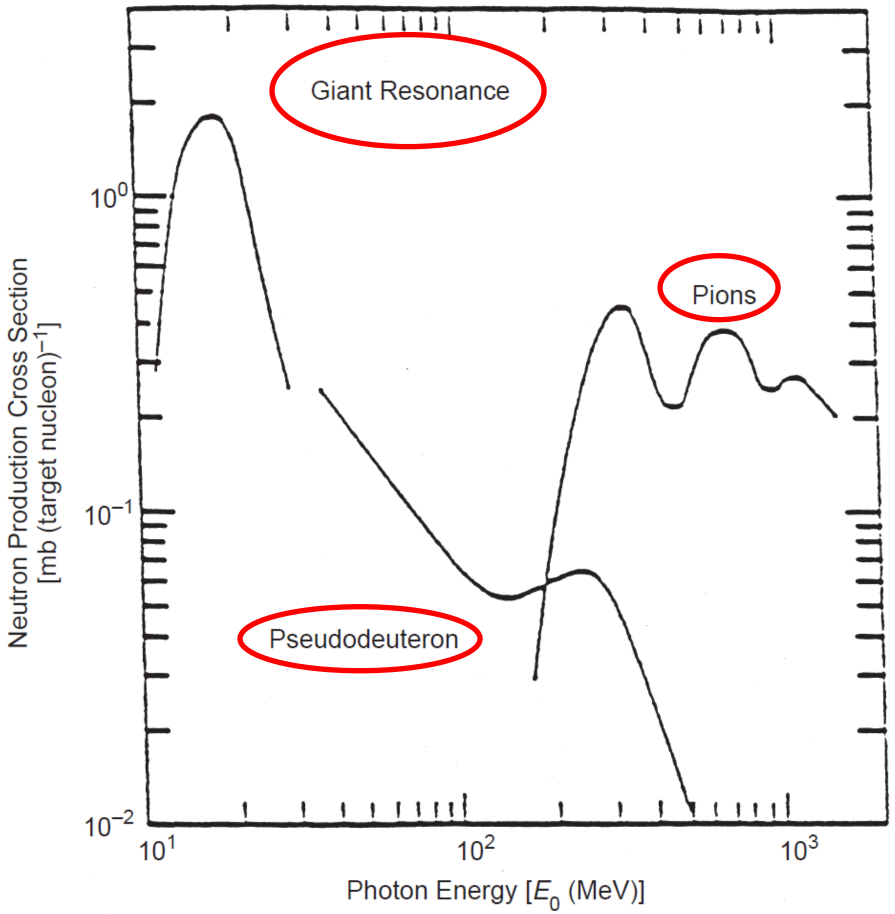
- ✓ Bremsstrahlung photons are very forward peaked (characteristic angle in radians = 0.511/E where E is the electron energy in MeV).
- ✓ Their yield increases with the increasing of electron energy.
- ✓ Bremsstrahlung photons emitted in the forward direction (0°) are the most energetic and penetrating, while bremsstrahlung photons emitted at wide angles are softer.




Bremsstrahlung yield from a high Z target.

# Neutrons

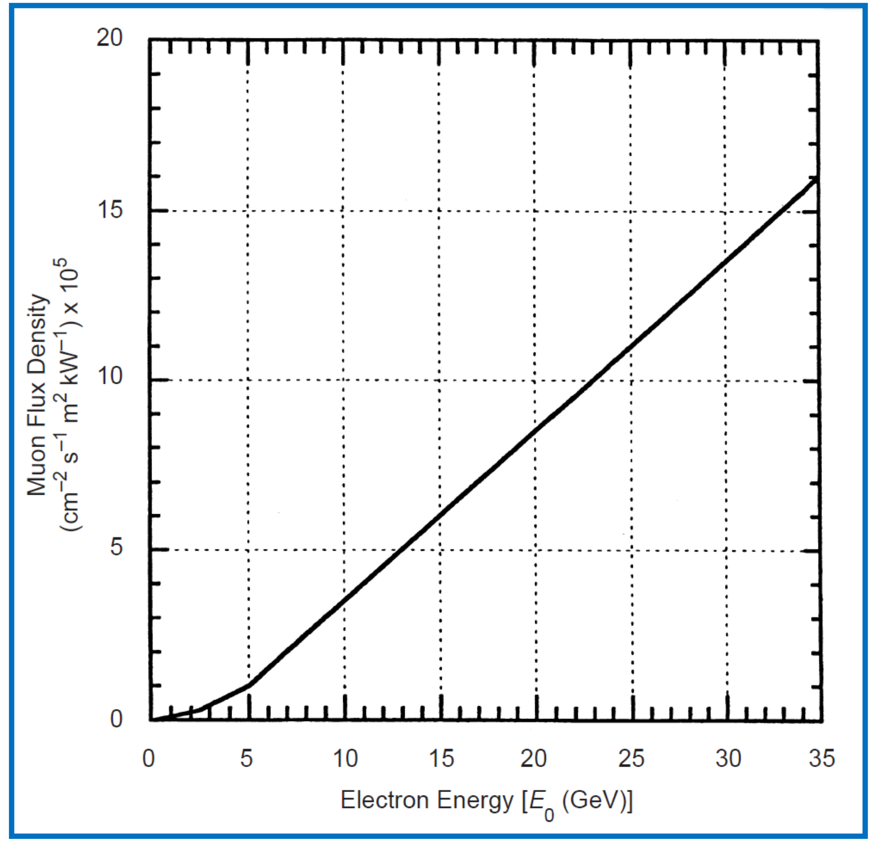
✓ Interacting with materials, the photons of the EM shower may produce neutrons: neutron production occurs above a threshold energy that varies from 10 to 19 MeV for high nuclei and from 4 to 6 MeV for heavy nuclei.




- **GR: a photon may interact with a nucleus to produce an excited compound nucleus that de-excites by the evaporation of a neutron.**
- **Pseudodeuteron reactions (above ~25MeV): the absorption of a photon by a proton-neutron pair in the nucleus may produce neutrons with energy between 10 and 100 MeV.**
- **Above ~200MeV a photon may interact with a nucleon to produce a pion plus a high energy neutron. Above 400 MeV a photon may interact with a nucleon pair to produce 2 pions and a neutron, or may interact with a nucleon pair ejecting 2 nucleons, either or both of which may be neutrons.**

# Muons

- ✓ Muon production occurs when the photon energy exceeds a threshold equal to $2m_{\mu}c^2$ (≈211MeV).
- ✓ Muon production is much less probable than electron-pair production and is extremely forward peaked (a few degrees).
- ✓ Due to their large mass, muons dissipate their energy mainly by collision processes.




**Muon flux density at 0° at 1 m from an unshielded iron target per kilowatt of electron beam power as a function of electron energy.**

# Induced radioactivity

- ✓ Induced radioactivity occurs when a previously stable material is made radioactive by exposure to high energy radiation.

- ✓ It may be produced by high energy gamma rays via photodisintegration reactions ($\gamma$,n), ($\gamma$,p), ($\gamma$,np), ($\gamma$,2n):

radiation
stable nucleus
unstable nucleus
neutron release

$$^{N}_{Z}A + \gamma = {}^{N-1}_{Z}B + n$$

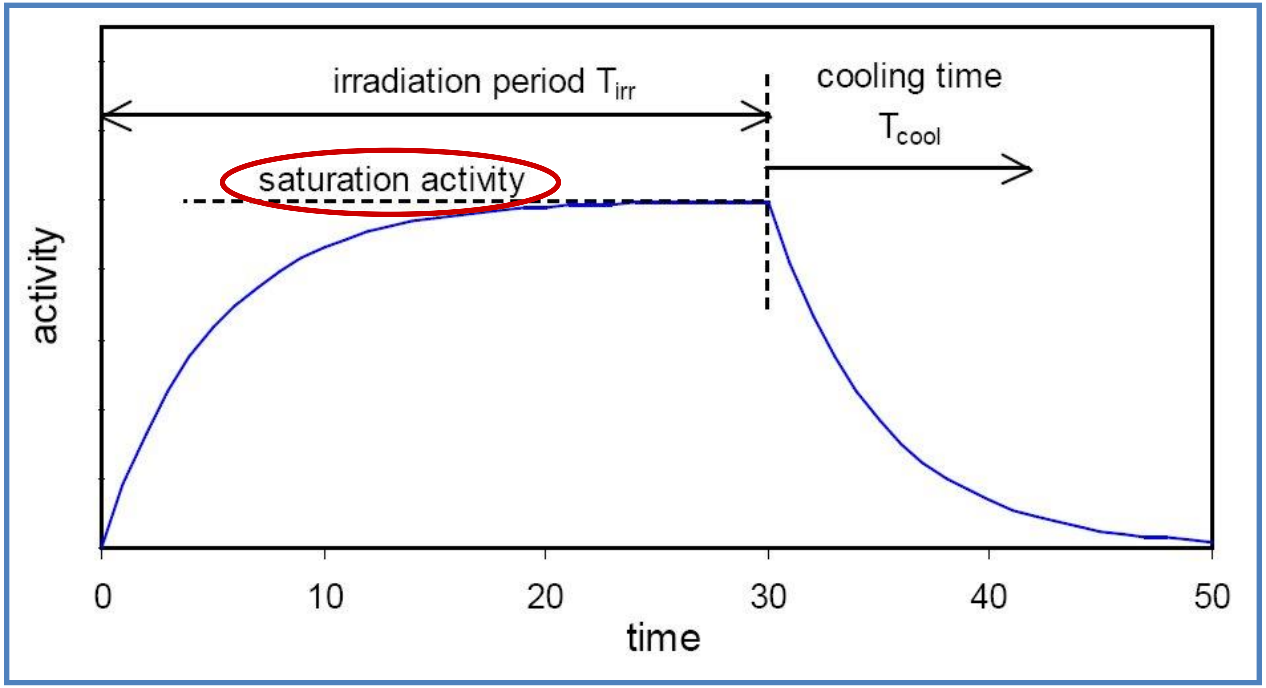
- ✓ These reactions have a minimum energy cut-off of 2 MeV (for H) and around 10 MeV for most heavy nuclei.

# Time evolution of induced radioactivity

- ✓ Induced radiation will not disappear immediately when the accelerator is switched off, but will decay with a characteristic decay constant.

**Activation formula:**

$$A_i(T_{irr}, T_{cool}) = \Phi N \sigma_i \left(1 - e^{-\frac{T_{irr}}{\tau_i}}\right) e^{-\frac{T_{cool}}{\tau_i}}$$




$A_i$: activity (Bq) per $cm^3$

$\Phi$: n° of particles hitting the target per $cm^2$ and per s

N: n° of nuclei per $cm^3$ in the target

$\sigma_i$: cross section for the production in the target of the $i^{th}$ isotope ($cm^2$)

$T_{irr}$: irradiation time (s)

$T_{cool}$: cooling time (s)

$\tau_i$: lifetime of the $i^{th}$ isotope (s)

Elettra Sincrotrone Trieste

# Saturation activities at high energy electron accelerators

**Material: Concrete**

| Radio-nuclide | $T_{1/2}$ | Threshold (MeV) | Parent isotope | Type | Saturation Activity (GBq / kW) |
|---|---|---|---|---|---|
| C-11 | 20.34 min | 18.72 | C-12 | (γ,n) | 0.13 |
| O-15 | 123 s | 15.67 | O-16 | (γ,n) | 96. |
| Na-22 | 2.62 a | 12.44 | Na-23 | (γ,n) | 3.7 |
| Mg-23 | 12.1 s | 16.55 | Mg-24 | (γ,n) | 0.27 |
| Al-26m | 6.37 s | 13.03 | Al-27 | (γ,n) | 0.034 |
| Si-27 | 4.14 s | 17.18 | Si-28 | (γ,n) | 74. |
| K-38 | 7.71 min | 13.08 | K-39 | (γ,n) | 3.7 |
| Fe-53 | 8.51 min | 13.62 | Fe-54 | (γ,n) | $3.7 \times 10^{-3}$ |

**Material: Copper**

| Radio-nuclide | $T_{1/2}$ | Threshold (MeV) | Parent isotope | Type | Saturation Activity (GBq / kW) |
|---|---|---|---|---|---|
| Co-58 | 71.3 d | 41.75 | Cu-63 | (γ,sp) | 24. |
| Co-58m | 9.2 h | 41.75 | Cu-63 | (γ,sp) | 24. |
| Co-60 | 5.263 a | 18.86 | Cu-63 | (γ,n2p) | 24. |
| Ni-63 | 92 a | 17.11 | Cu-65 | (γ,np) | 17. |
| Cu-61 | 3.32 h | 19.73 | Cu-63 | (γ,2n) | 32. |
| Cu-62 | 9.76 min | 10.84 | Cu-63 | (γ,n) | 407. |
| Cu-64 | 12.80 h | 9.91 | Cu-65 | (γ,n) | 185. |
| Cu-66 | 5.10 min | – | Cu-65 | (n,γ) | – |

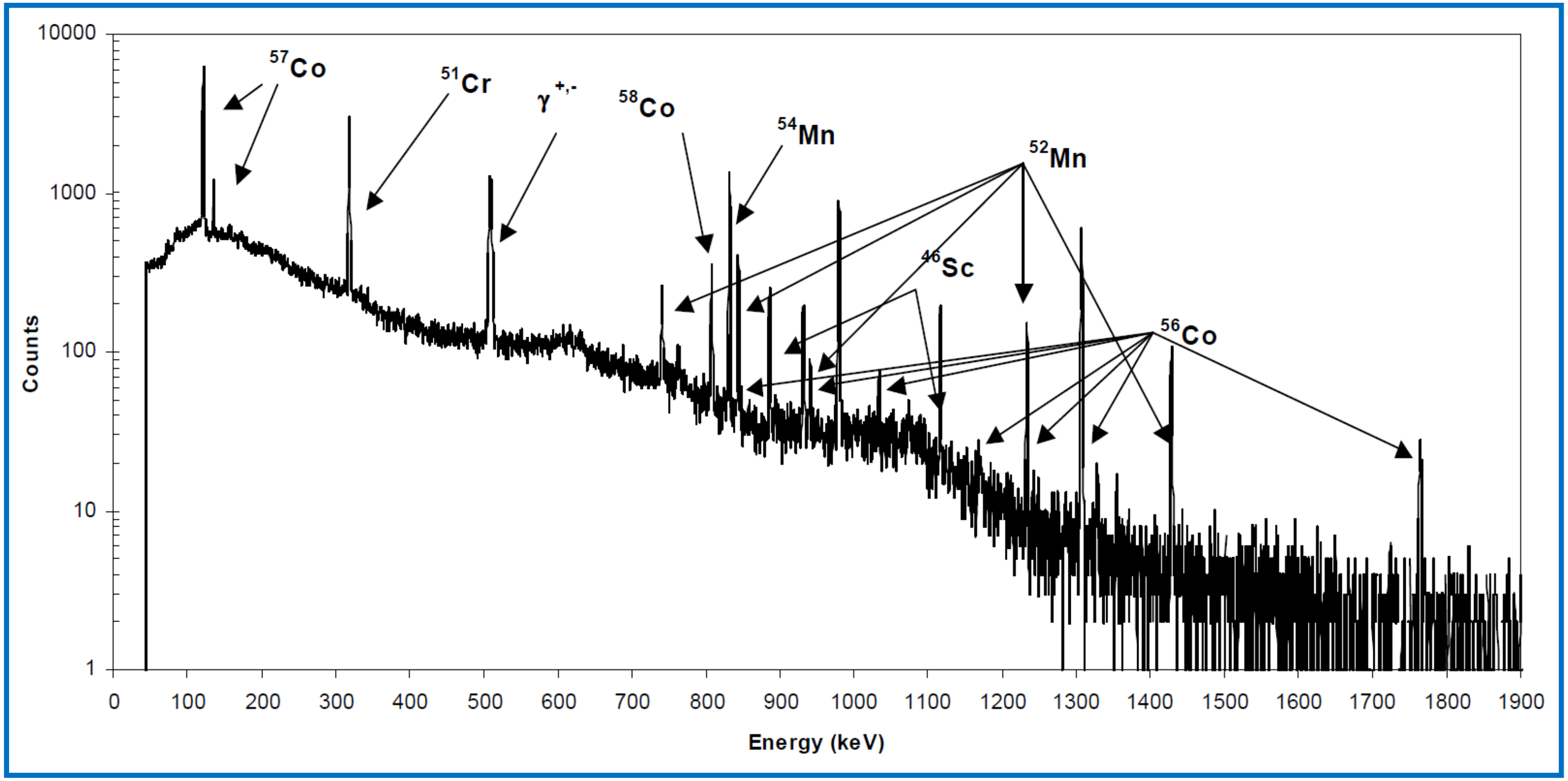
**Material: Iron**

| Radio-nuclide | $T_{1/2}$ | Threshold (MeV) | Parent isotope | Type | Saturation Activity (GBq / kW) |
|---|---|---|---|---|---|
| Sc-46 | 83.9 d | 37.41 | Fe-54 | (γ,sp) | 7.4 |
| V-48 | 16.0 d | 25.86 | Fe-54 | (γ,sp) | 15. |
| Cr-51 | 27.8 d | 19.74 | Fe-54 | (γ,sp) | 15. |
| Mn-52 | 5.60 d | 20.89 | Fe-54 | (γ,np) | 1.3 |
| Mn-52m | 21.1 min | 20.89 | Fe-54 | (γ,np) | 1.3 |
| Mn-54 | 303 d | 20.42 | Fe-56 | (γ,np) | 22. |
| Mn-56 | 2.567 h | 10.57 | Fe-57 | (γ,p) | 1.2 |
| Fe-52 | 8.2 h | 24.06 | Fe-54 | (γ,2n) | 2.1 |
| Fe-53 | 8.51 min | 13.62 | Fe-54 | (γ,n) | 27. |
| Fe-55 | 2.60 a | 11.21 | Fe-56 | (γ,n) | 490. |
| Fe-59 | 45.6 d | – | Fe-58 | (n,γ) | – |

**Material: Aluminium**

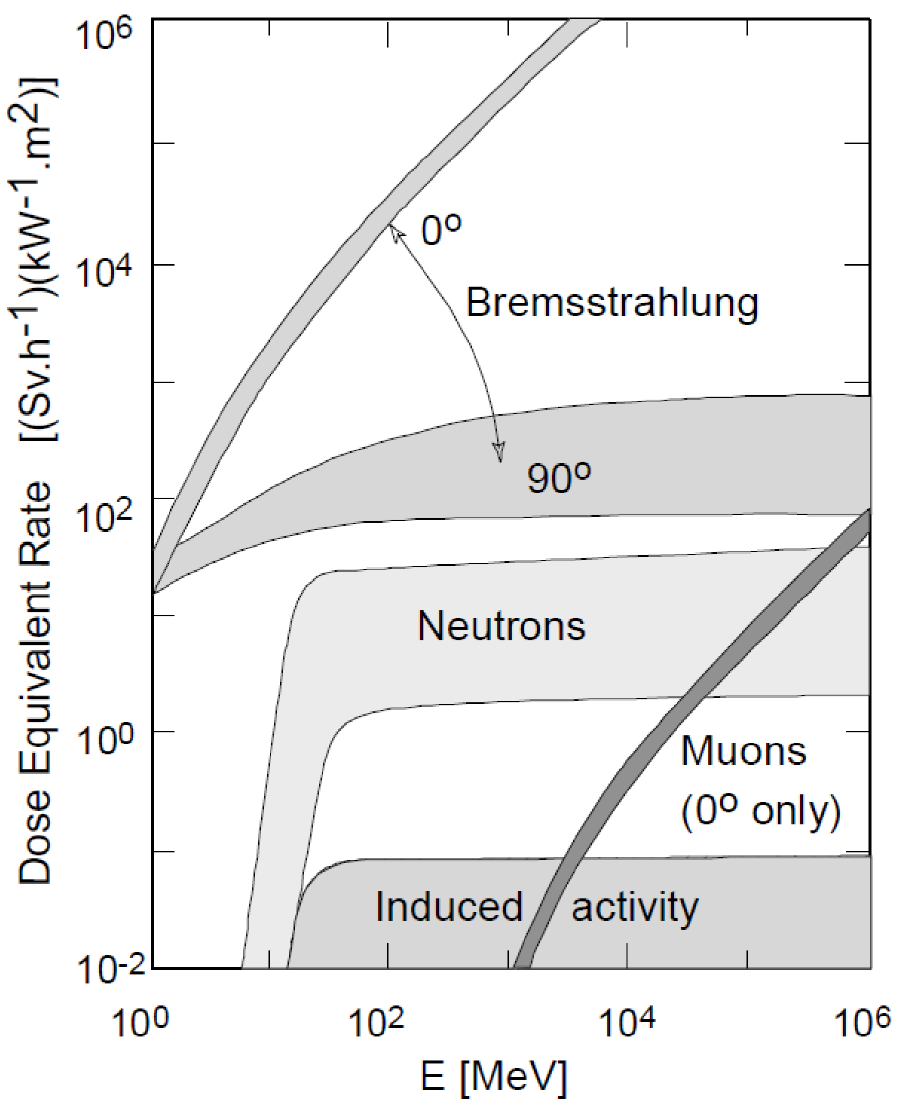
| Radio-nuclide | $T_{1/2}$ | Threshold (MeV) | Parent isotope | Type | Saturation Activity (GBq / kW) |
|---|---|---|---|---|---|
| Be-7 | 53.6 d | 32.95 | Al-27 | (γ,sp) | 4.8 |
| C-11 | 20.34 min | 33.53 | Al-27 | (γ,sp) | 1.9 |
| N-13 | 9.96 min | 25.56 | Al-27 | (γ,sp) | 0.5 |
| O-15 | 123 s | 44.43 | Al-27 | (γ,sp) | 2.5 |
| F-18 | 109.7 min | 34.39 | Al-27 | (γ,sp) | 5.2 |
| Ne-24 | 3.38 min | 33.11 | Al-27 | (γ,3p) | 0.11 |
| Na-22 | 2.62 a | 22.51 | Al-27 | (γ,3n2p) | 9.3 |
| Na-24 | 14.96 h | 23.71 | Al-27 | (γ,1n2p) | 10. |
| Al-25 | 7.24 s | 24.41 | Al-27 | (γ,2n) | 1.4 |
| Al-26 | $7.4 \times 10^{5}$ a | 13.03 | Al-27 | (γ,n) | 330. |
| Al-26m | 6.37 s | 13.03 | Al-27 | (γ,n) | 330. |
| Mg-27 | 9.46 min | 140 | Al-27 | $(\gamma,\pi^{+})$ | 0.59 |

# Induced radioactivity: an example




**Example of activation spectrum measured on a stainlss steel vessel at the ESRF.**

# Summary of radiation components



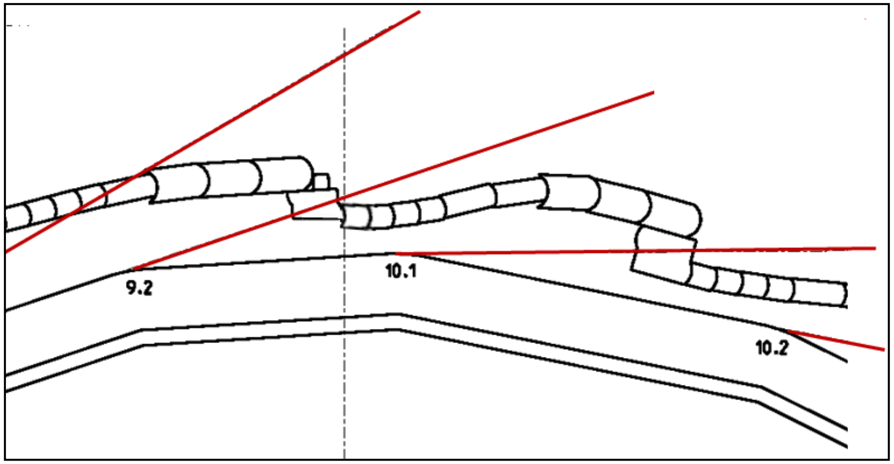

**Dose equivalent rates per unit beam power to be expected from an electron beam striking beam line components, in the absence of shielding.**
**The widths of the bands for different types of radiation indicate expected variations dependent on the type and thickness of target material**
**(Rad. Prot. Dosimetry, Vol.96, n.4, 2001)**

# Accelerator shielding design

- ✓ The thickness of radiation shielding can be calculated through analytical formulae based on conservative source-term definition for the different radiation components or through Monte-Carlo simulations.
- ✓ In both cases, one of the most critical point is the definition of the beam loss scenarios in correspondence to the different modes of operation of the accelerator ("normal" operation, injection mis-steering, accident scenarios, etc.). Area occupancy and accelerator working load are other important parameters to take into account.
- ✓ Shielding thickness is generally determined by beam losses produced during injection or mis-steering of the injected beam rather than by losses produced during stored-beam operation.

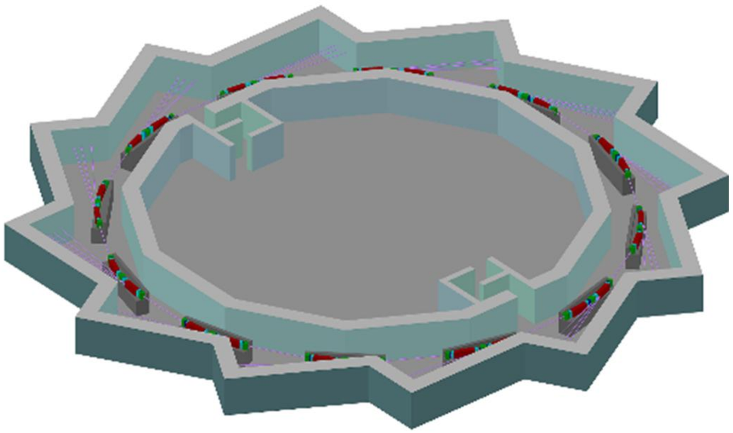
# Examples of ring shielding design

**Elettra**





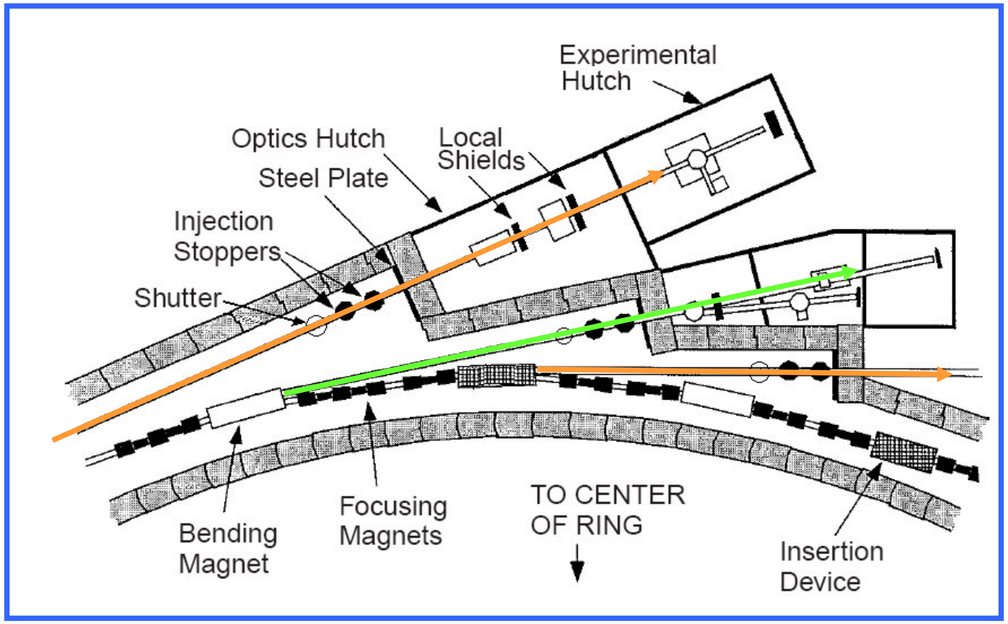
**SOLARIS storage ring in Poland**



# Radiation protection issues at the beamlines: refill injection

- ✓ The beamlines are constructed tangentially to the storage ring: synchrotron radiation is <u>extracted through the ring shielding</u> inside vacuum chambers.

- ✓ During refill injection, specific devices, called <u>*stoppers*</u>, installed in the beamline front-end, <u>are kept closed</u> to stop the forward bremsstrahlung photons (→ special considerations must be done for top-up operation).



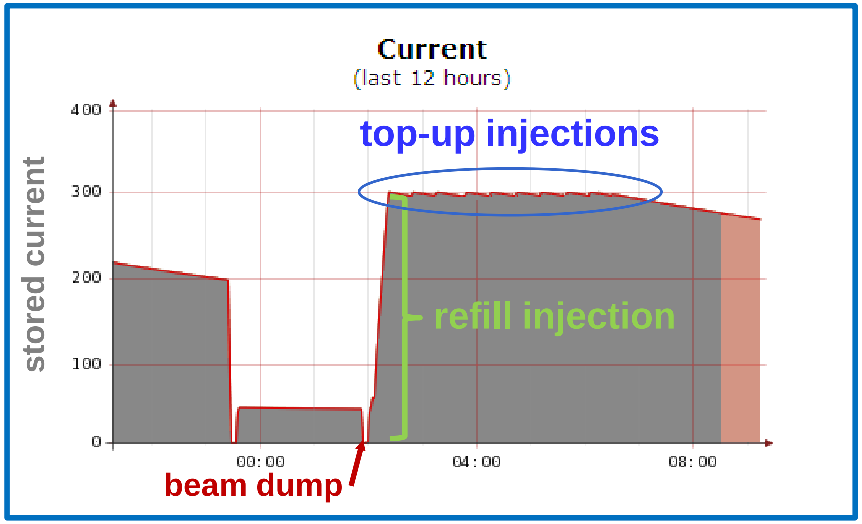
# Radiation protection issues at the beamlines: stored beam

- ✓ During stored beam operation, beamline stoppers are open and the bremsstrahlung photons produced by the interaction of the electron beam with the residual gas in the ring vacuum chamber may propagate along the beamline.

- ✓ Bremsstrahlung intensity is proportional to about $E^{2.5}$ (lectron energy), I (stored current), P (vacuum chamber pressure) and to the length of the air column in the straight section of the ring which is aligned with the beamline → more critic for insertion device than for bending magnet beamlines.

- ✓ When mirrors or monochromators are used to deflect synchrotron light horizontally or vertically, local lead shielding can be used behind these devices to stop bremsstrahlung radiation.

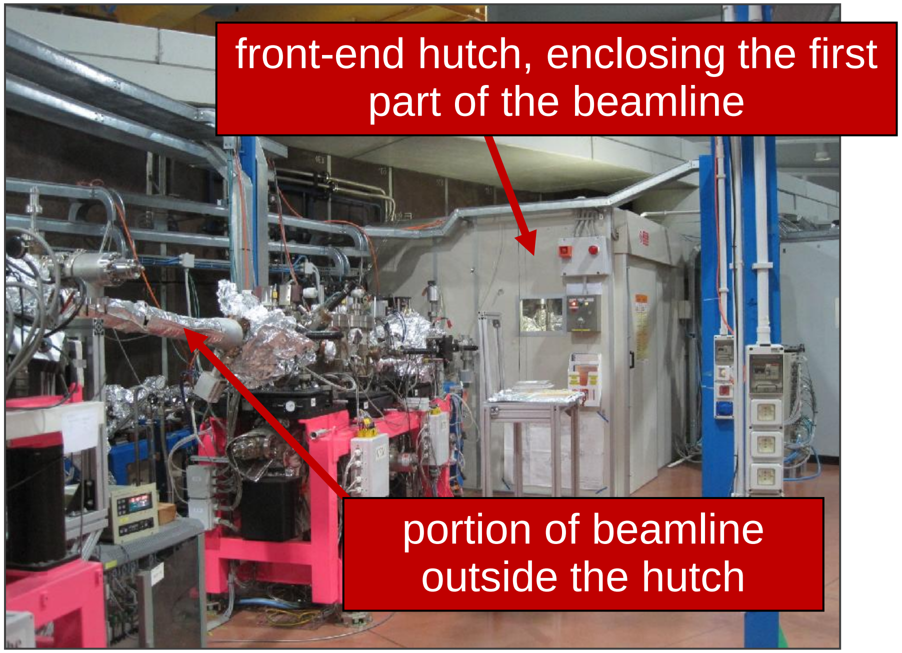
# Radiation protection issues at the beamlines: top-up mode




- ✓ Top-up consists of frequent injection of electrons inside the ring to keep constant the stored current, while the beamlines are open to the users.
- ✓ Elettra specific interlocks:
  - hardware key
  - minimum stored current requested inside the ring
  - matching between energy settings of the booster-to-storage-ring-transfer-line dipoles and the storage-ring dipoles
  - limit on the maximum current per pulse extracted from the booster
  - limit on the maximum current that can be lost over short periods (few seconds) and over long periods (1 hour)
- ✓ Further interlocks are produced by the beamlines' radiation monitors.
- ✓ Dedicated radiation surveys have been carried out to evaluate top-up impact on beamline shielding.

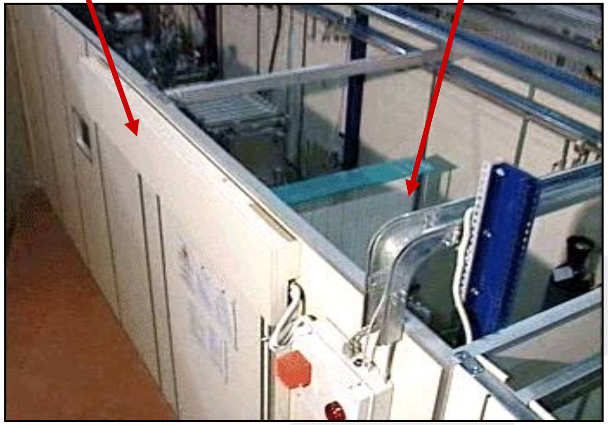
# Beamline shielding

- ✓ Depending on the working energy and on its specific characteristics, a beamline can be partially or entirely enclosed inside shielding walls, called hutch; a beamline can have one or more hutches.




# Materials for radiation shielding

- ✓ The choice of shielding material depends mainly on the type of radiation that have to be shielded, but also on other criteria, such as structural properties, cost, availability of space, etc.
- ✓ Concrete is one of the most commonly used material where mixed radiation fields are produced.
- ✓ Lead is commonly used to attenuate photons, thanks to its high density, whereas dense polyethylene is preferred where neutrons are the most important component.

# Personnel Safety Systems (PSSs)

✓ Accelerator and beamlines Personnel Safety Systems are specifically developed to protect personnel from radiation hazards → commonly based on hardwired relay logic or on Programmable Logical Controllers (PLCs).

**Their purpose is to guarantee that:**

- no prompt radiation can be switched on in the accelerator tunnels or in the beamline areas if someone is present.
- if someone is detected during beam operation, all sources of prompt radiation are immediately switched off.

✓ The PSSs include visible and audible signals, optical barriers, mechanical or magnetic switches, etc.


Elettra Sincrotrone Trieste

# PSS characteristics

- ✓ PSS design is based on the following criteria:

**REDUNDANCY:** is the duplication or repetition of elements to provide alternative functional channels in case of failure.

**DIVERSIFICATION:** duplicated elements having the same function are realized, if possible, with different technologies.

**FAIL-SAFE:** in case of a safety device failure, the system must automatically turn to a safe condition.

- ✓ PSSs normally are clearly separated from the control system of the accelerator or of the beamline to avoid conflicts related to the maintenance of the systems.
- ✓ A re-testing of the PSS should be foreseen after any intervention on it.

Elettra Sincrotrone Trieste

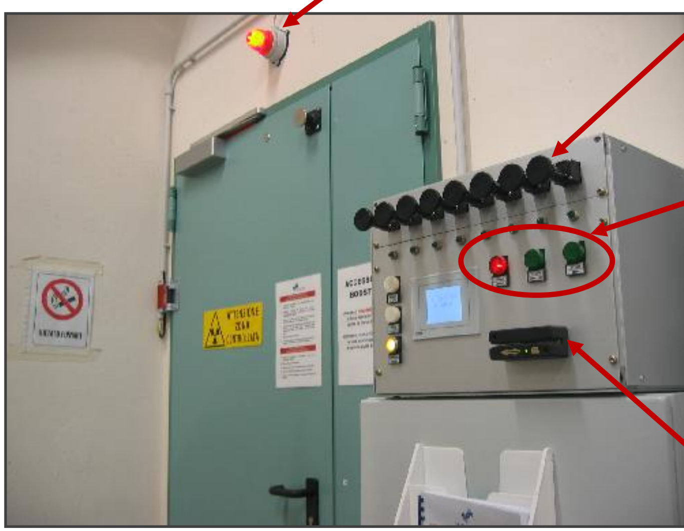
# Access procedure to the accelerator tunnels

- ✓ Access procedure commonly foresees the use of an individual badge or a safety key or other type of biometric data acquisition → the aim is to keep under control the number of persons entering the accelerator tunnel.

- ✓ No permission to switch on the beam is delivered to the PSS until everyone has left the area.

**Lamp for “Door locked”**

**Safety keys or “baton”**




**Lamp for “Forbidden access”**

**Lamp for “Controlled access”**

**Lamp for “Free access”**

**Badge reader**

# Search procedure for the accelerator tunnels

- ✓ Search is a <u>visual inspection</u> that must guarantee that nobody is left in hazardous areas before re-starting operations with the beam.

- ✓ The search buttons position and number should guarantee that <u>the search operator spans the entire area to check</u>.


End of the search

↓

Siren and/or flashing lights for a certain period of time

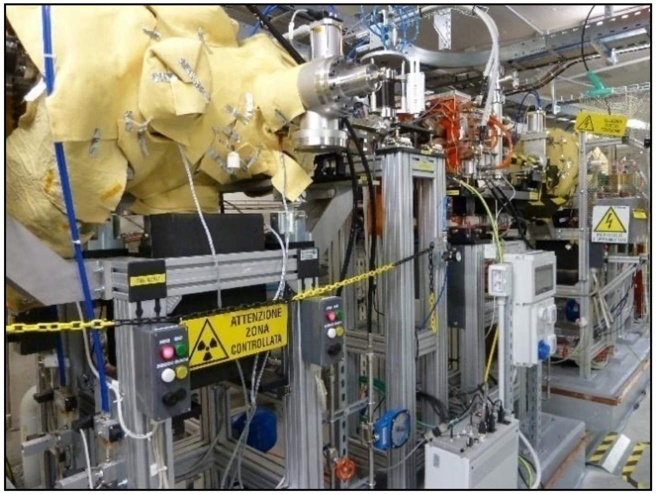
↓

Beam enabled

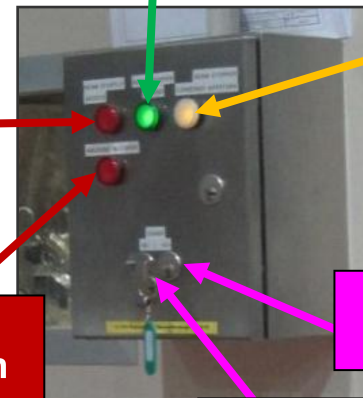
The aim is to allow people, left accidentally inside the tunnel, to <u>press an emergency stop</u> or <u>to get out of the risk area</u>.

# Shutdown procedure for the accelerator tunnels

- ✓ Shutdown procedure consists of a radiation survey of the accelerator components to evaluate the radiological risk tied to induced radioactivity.
- ✓ Areas affected by induced radioactivity are fenced and marked with signs. Access to these areas is regulated through radiation protection rules.



# The PSS of Elettra beamlines' hutches


**INSIDE THE HUTCH:**

**movement sensor**

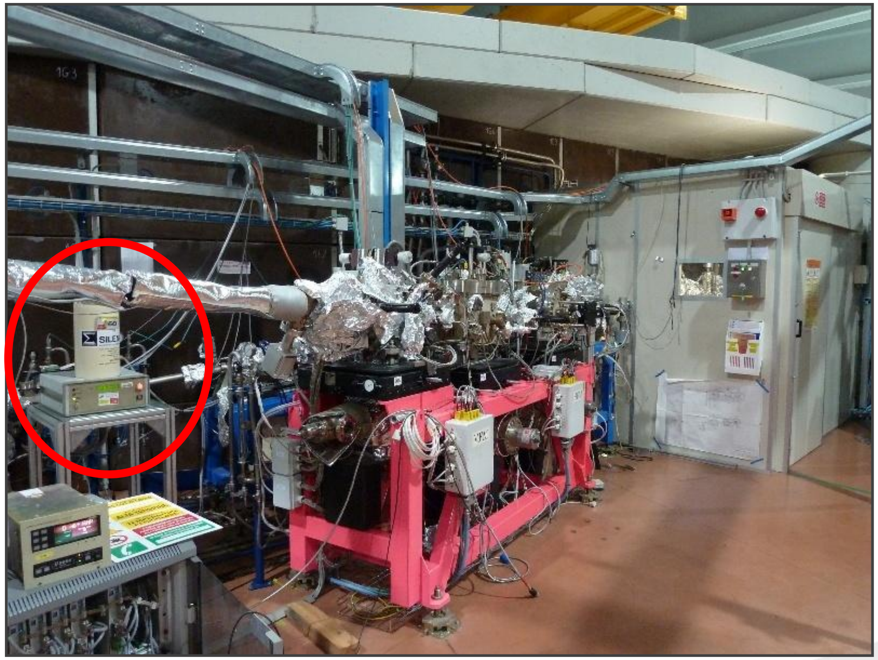
**emergency button**

**search button**

# Radiation monitoring outside the accelerator tunnels

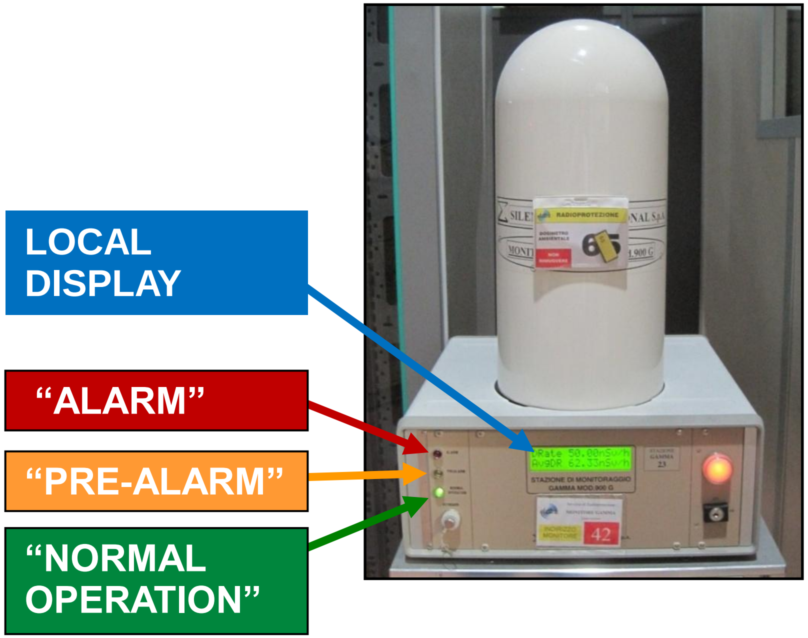
- ✓ Reliable and accurate measurements are possible only if the production and distribution of radiation fields are well known and if the characteristics (and limitations) of instrumentations are well understood.

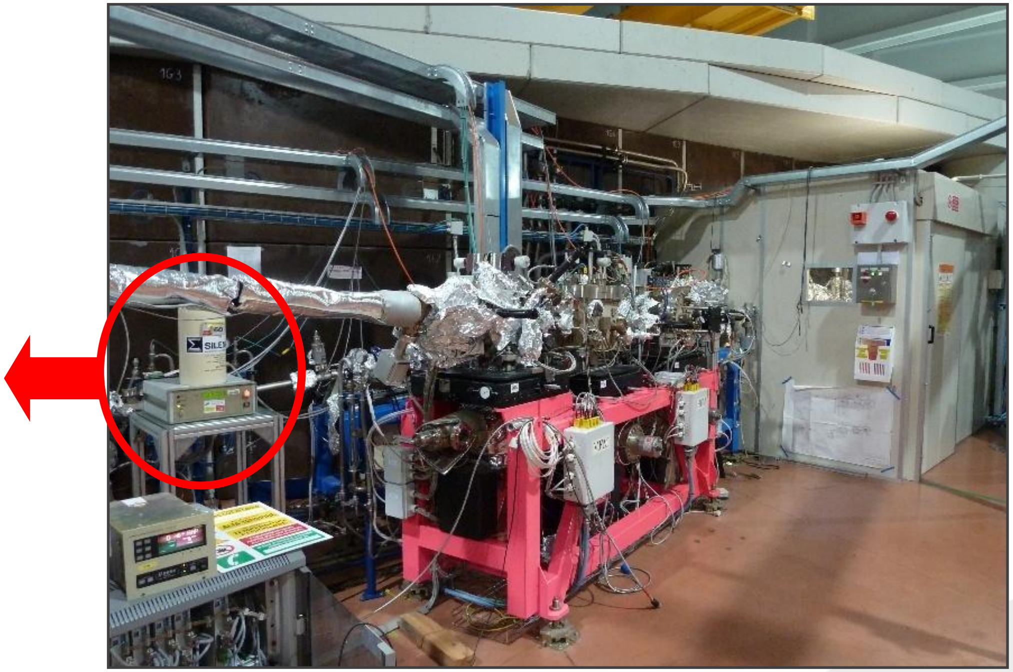
- ✓ At synchrotron facilities radiation monitoring can be complex because radiation fields are not constant, but largely depend on the accelerator operation parameters.



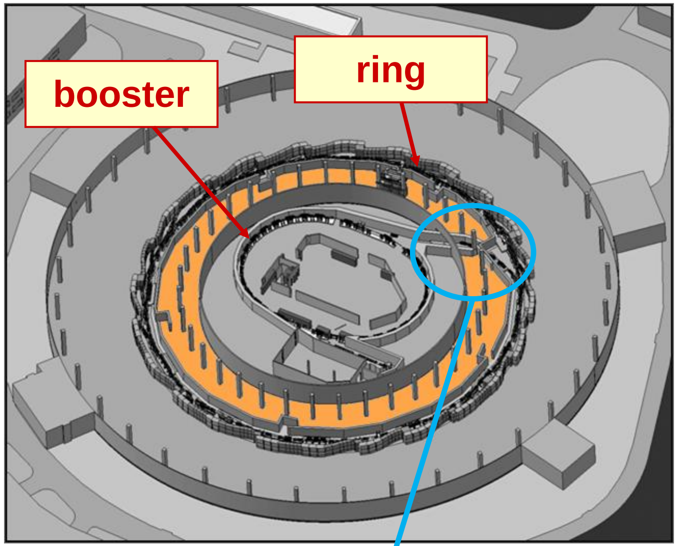
# Interlocked radiation monitors

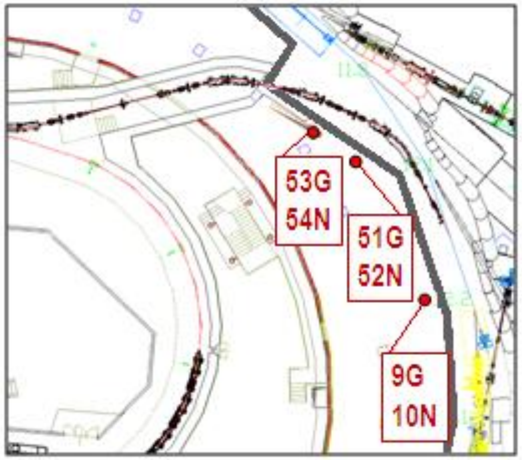
- ✓ Radiation monitoring is commonly based on ionization chambers with local and remote readout, and with alarm displays.
- ✓ Area monitors can be interlocked to the accelerator or beamline PSS to stop all the operations with the beam in case of alarm.



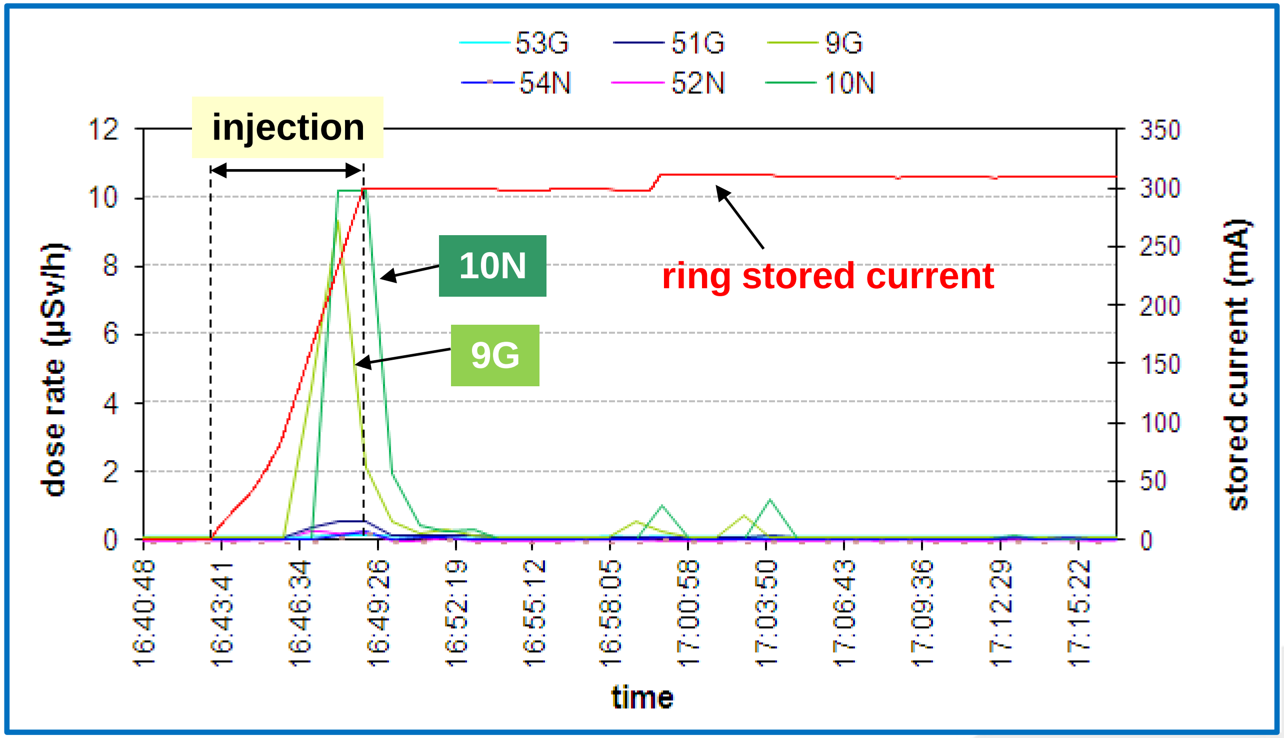



# Radiation doserate outside the accelerator tunnels: example 1

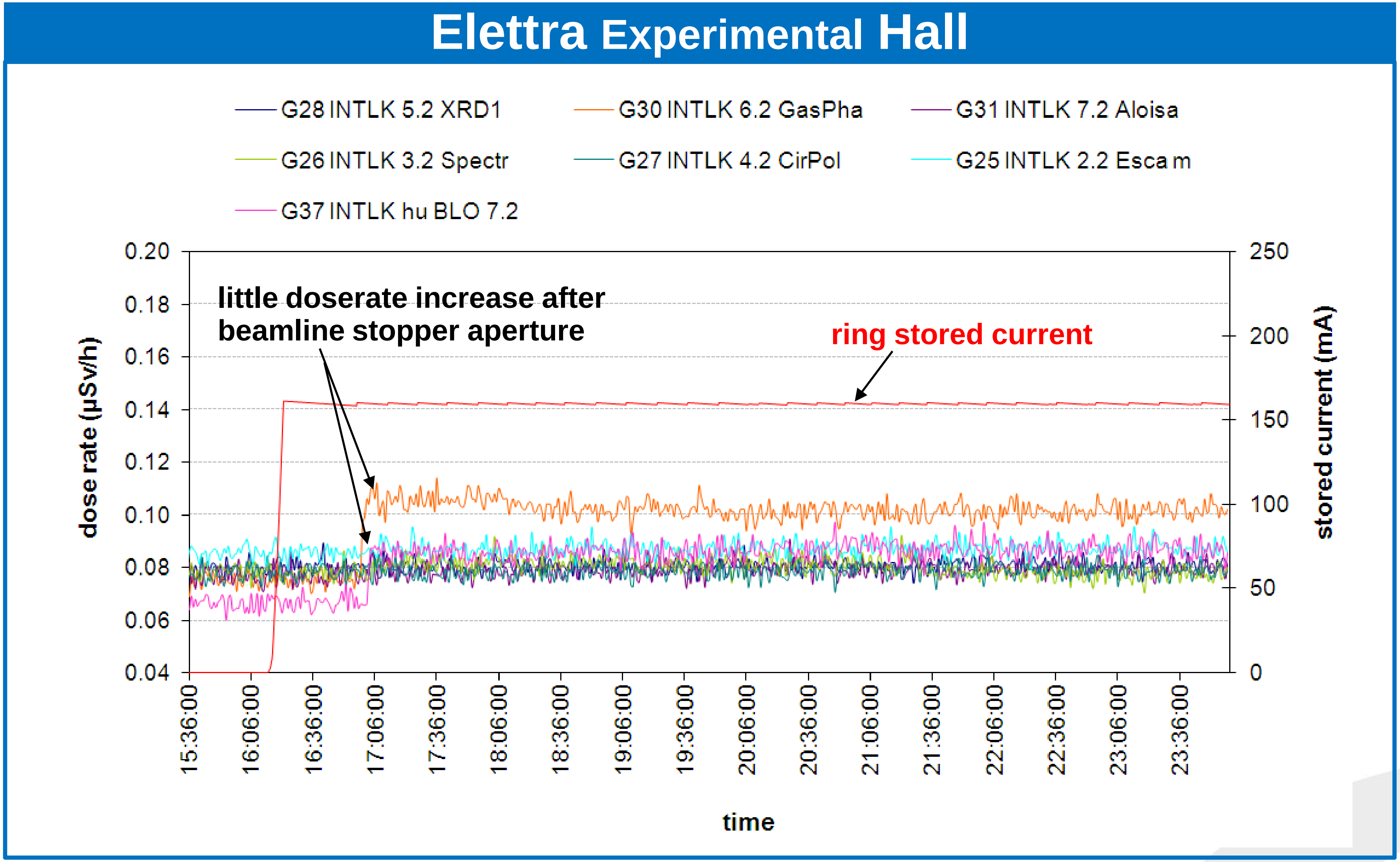



**Ring Service Area**



# Radiation doserate outside the accelerator tunnels: example 2

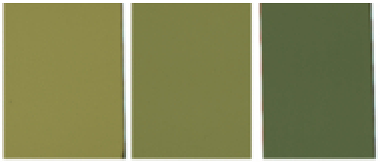


Elettra Sincrotrone Trieste

# Radiation surveys

- ✓ Radiation surveys with portable instruments (ionisation chambers, Geiger-Mueller counters, neutron counters) must be always performed when changes that may affect radiation levels or exposure conditions are made in accelerator/beamline configuration, shielding, or occupancy.

- ✓ Passive dosimeters:



# Area classification

✓ Areas in which exposure risk to ionizing radiation for a worker may exceed one of the limits fixed for the public <u>have to be classified</u> in accordance with applicable laws.

| | Limits for the public [mSv/year] | Classified areas [mSv/year] | |
|---|---|---|---|
| | | Supervised areas | Controlled areas |
| **Effective dose** | **1** | **1-6** | **> 6** |
| **Eye** | **15** | **15-45** | **> 45** |
| **Skin** | **50** | **50-150** | **> 150** |
| **Hands, forearms, feet and ankles** | **50** | **50-150** | **> 150** |



✓ Radiation areas should be <u>fenced</u> and <u>marked with signs</u>; workers and visitors should be <u>informed</u> of hazards and of <u>radiation protection rules</u> regulating access to the areas (training, dosimeter wearing, temporal limits on permanence, etc.)

Elettra Sincrotrone Trieste

# Worker classification

✓ Individuals for whom the radiation exposure risk may exceed one of the limits fixed for the public <u>have to be classified</u> as radiation workers (in Italy: “B category” or “A category” radiation workers).

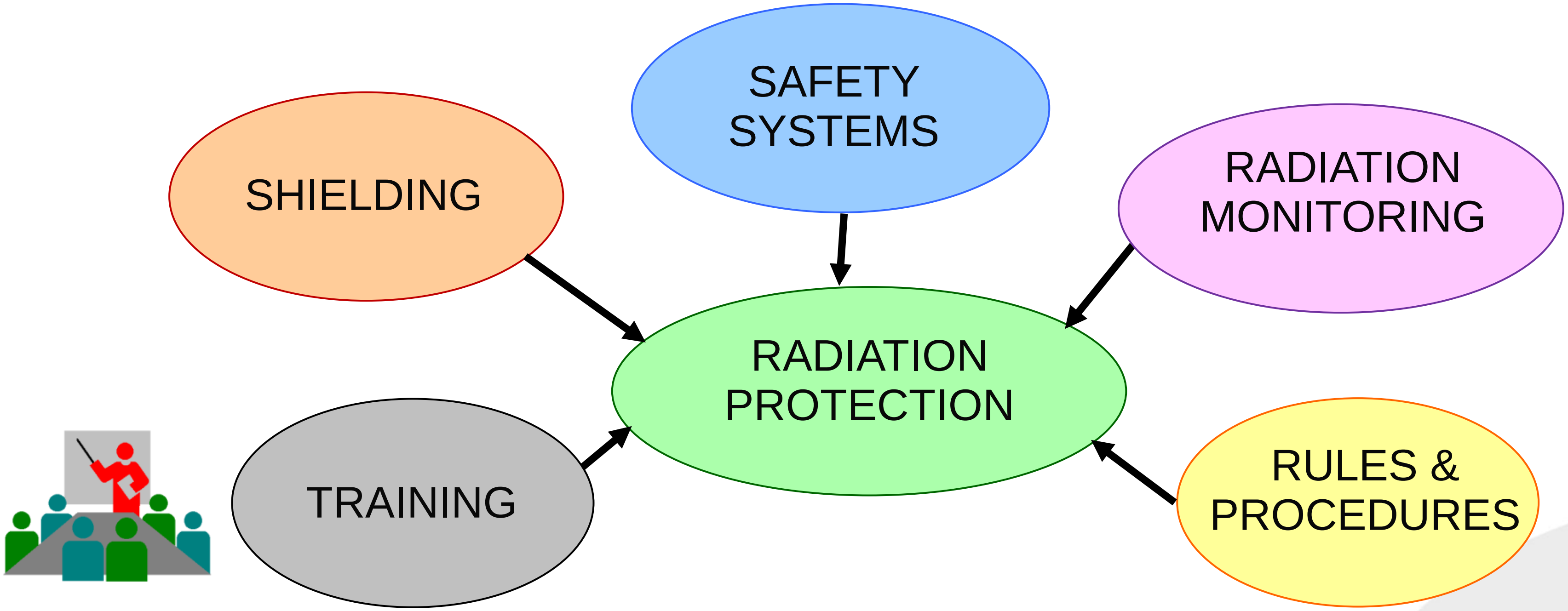
| | Limits for the public [mSv/year] | Radiation workers [mSv/year] | |
|---|---|---|---|
| | | **B category** | **A category** |
| **Effective dose** | **1** | **1-6** | **6-20** |
| **Eye** | **15** | **15-45** | **45-150** |
| **Skin** | **50** | **50-150** | **150-500** |
| **Hands, forearms, feet and ankles** | **50** | **50-150** | **150-500** |

**A category workers** → **(at least) semestral medical checks + individual dosimetry**

**B category workers** → **(at least) annual medical checks + individual/environmental dosimetry**

# Worker training

- ✓ Employees, contractors, users and visitors should receive a training commensurate with the radiation hazards associated with their tasks and responsibilities.
- ✓ Training is a fundamental part of the radiological risk management, because permits to keep under control the “human factor” and to teach, discuss and share rules and procedures.



Elettra
Sincrotrone
Trieste

Thanks for your attention…
questions?


www.elettra.eu