POLITECNICO MILANO 1863
DIPARTIMENTO DI ENERGIA

Radiation protection at medium- and high-energy particle accelerators

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Lecture outline

- Radiation fields generated by the operation of high-energy lepton and hadron accelerators
- Prompt radiation and induced radioactivity
- Fixed and portable instrumentation for area monitoring
- Individual dosimetry
- Operational radiation protection
- Radioactive waste and free release (clearance) in Switzerland

Linear accelerators (linac), cyclotrons and synchrotrons

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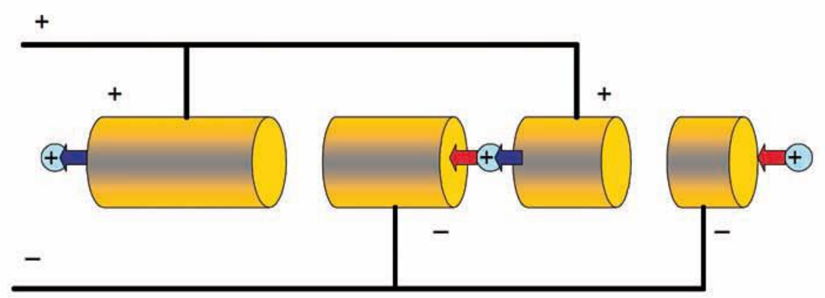

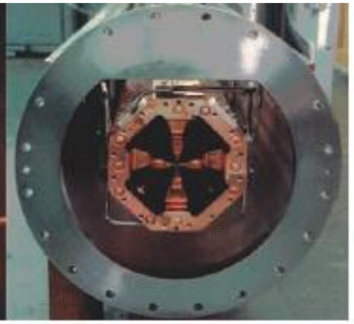

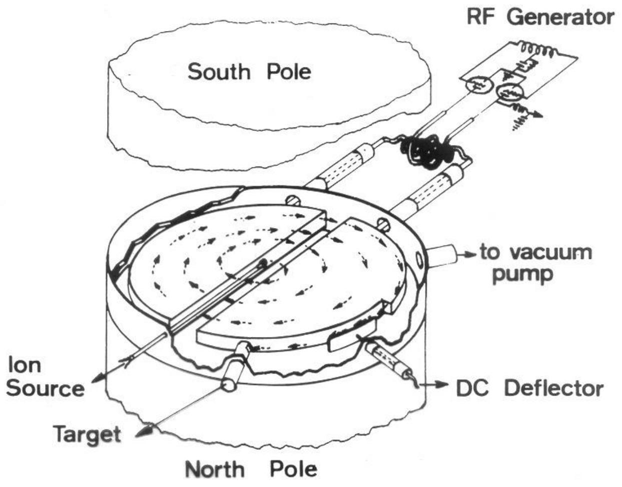

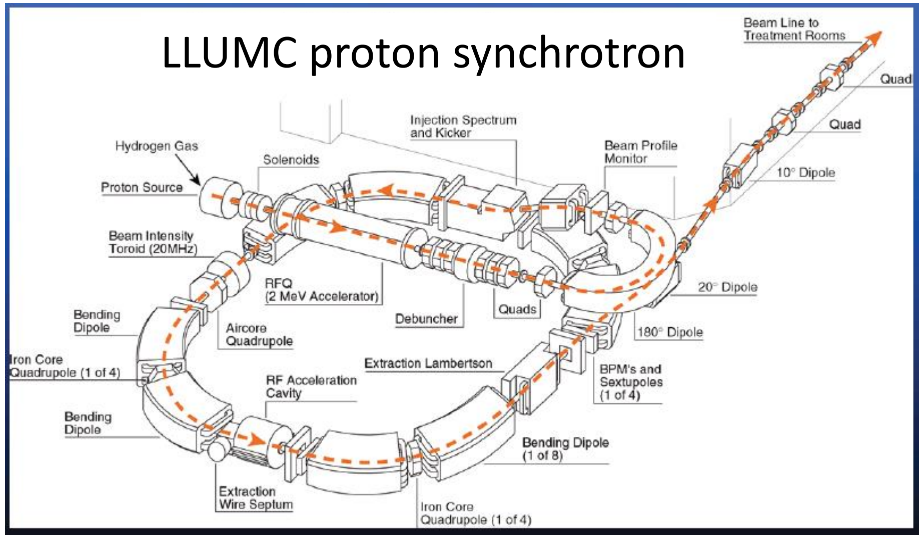

LLUMC proton synchrotron


CNAO ion synchrotron

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The parameters which most directly affect radiological safety are:

- Particle type and energy E_0
- Average beam power P

average beam current

$$P[W] = E_0[MeV] \times < I > [\mu A]$$

$$I\ [A] = N_p \times q_e \times N_{turns} / t$$

Radiation protection quantities such as dose rate or shielding thickness are generally NOT simple functions of energy E_0.

At a given energy E_0, the dose rate is directly proportional to average beam power P (i.e., to the number of "lost" particles).

With a LINAC, the Duty Factor DF is the fraction of operating time during which the LINAC is producing radiation.

$DF = p \times T_p$ p = pulse repetition rate [Hz]

T_p = pulse length [s]

With a synchrotron, the relevant parameters are repetition rate and flat top duration.

This is important with respect to radiation measurements

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Of the various particles generated by a target bombarded by a high-energy beam, those contributing to the dose past a shield are:

- neutrons
- photons
- muons (heavy electrons, ≈ 200 times the electron mass)

At energies > 10 GeV muons becomes important (at ≈ 100 GeV they can dominate some radiation environments)

Muon shielding completely dominates the forward shielding requirements at very high energies (this is why very-high energy accelerators are installed underground)

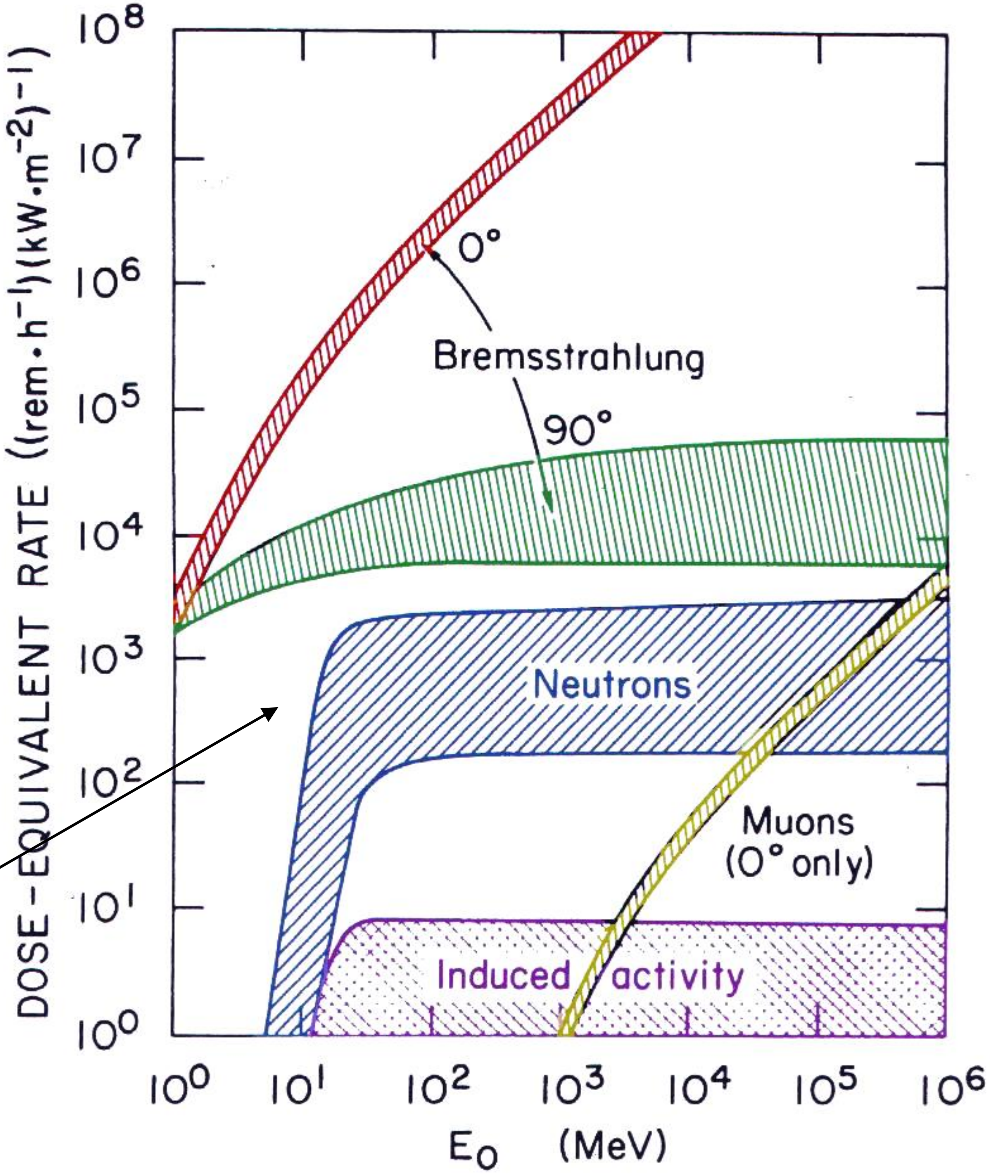
For some more information, click here

Prompt radiation at electron (lepton) accelerators

Dose equivalent rate at 1 m from target where 1 kW of e⁻ beam is lost

Inverse square dependence on distance (only approximately true)

For most materials, energy threshold for neutron production ~ 6-13 MeV (with some notable exceptions)



(plot from IAEA Technical Report no. 188, 1979)16

A recall of some basics: how to reduce external exposure

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- **Distance**: the dose rate decreases with the inverse squared of the distance (**from a point-like source**)

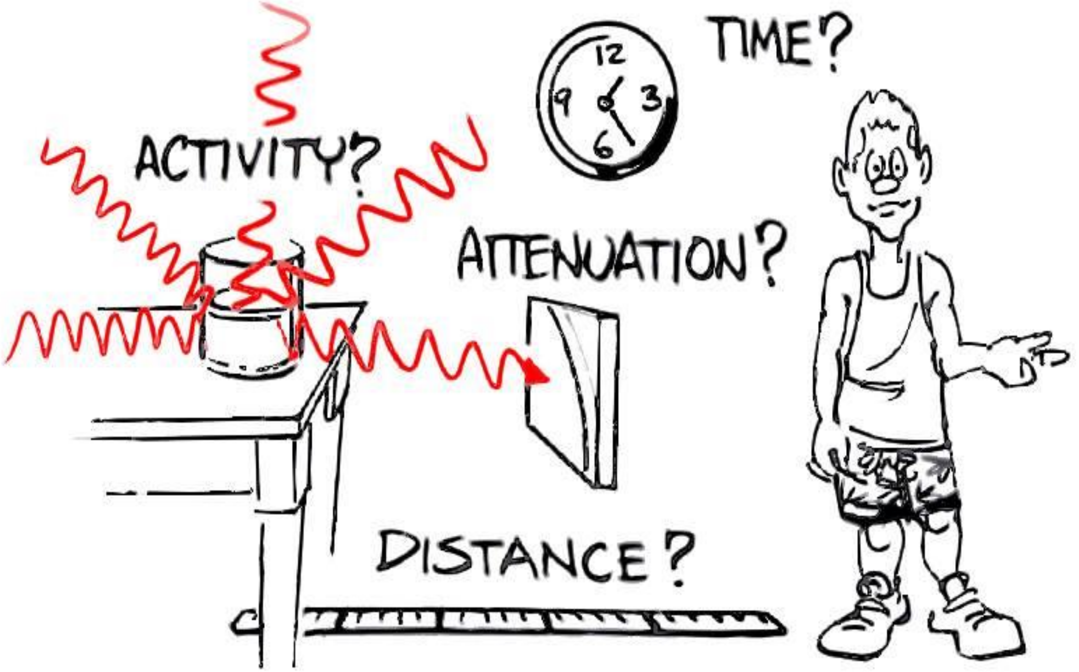
Very important at short distance - Factor of 100 between 1 cm and 10 cm (use of tongs/tweezers)

- **Time**: the dose is proportional to the time spent close to the source

  D = dD/dt x t

- **Shielding**: the dose rate approximately reduces as exp(-d/λ)

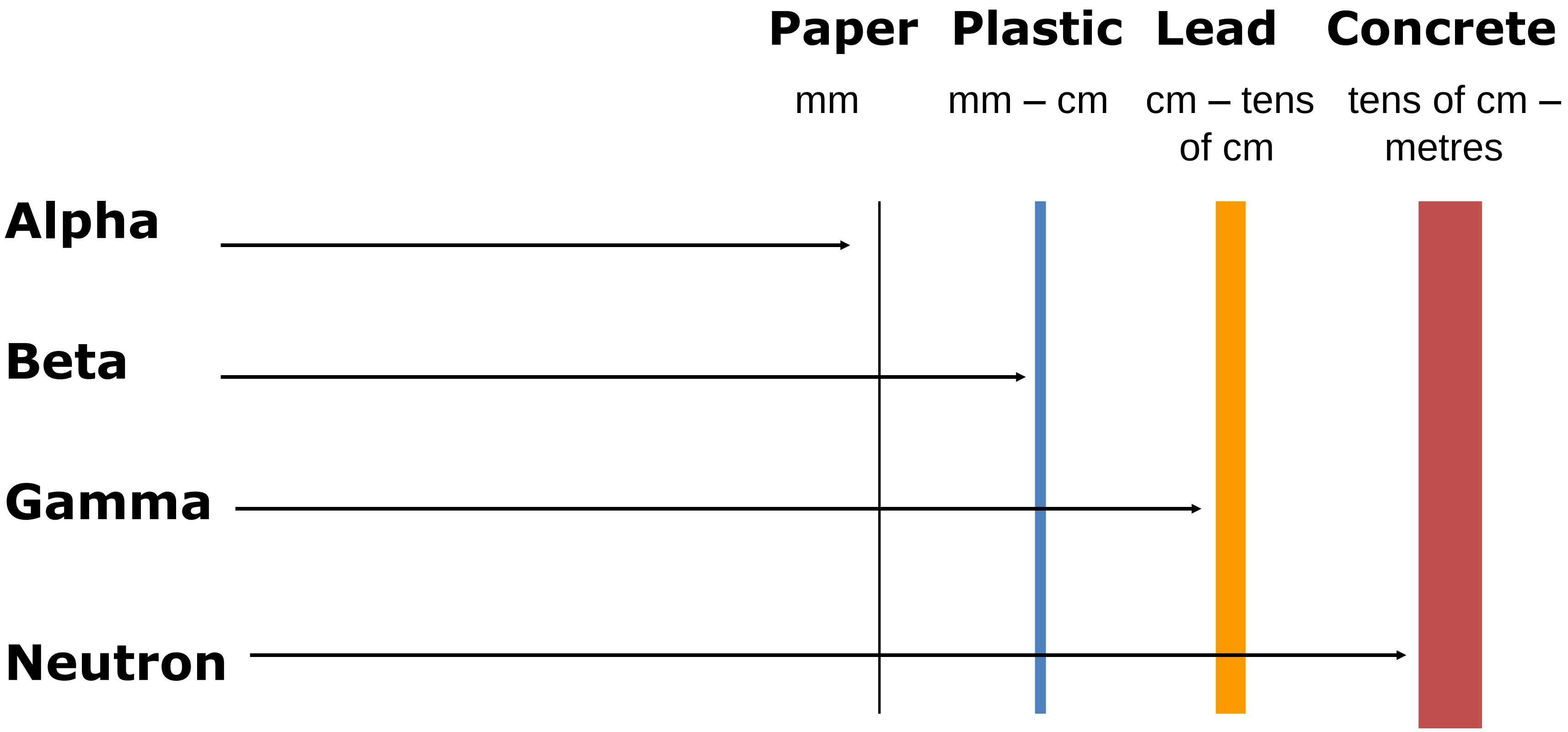
  λ = shielding properties of the material



For β radiation: plexiglass
For γ radiation: iron or lead
For n: concrete

A recall of some basics: absorption / attenuation of radiation

Qualitative!



Beta sources are usually shielded with Plexiglas, gamma sources with lead

CERN accelerator complex: 13 accelerators (12 + 1)

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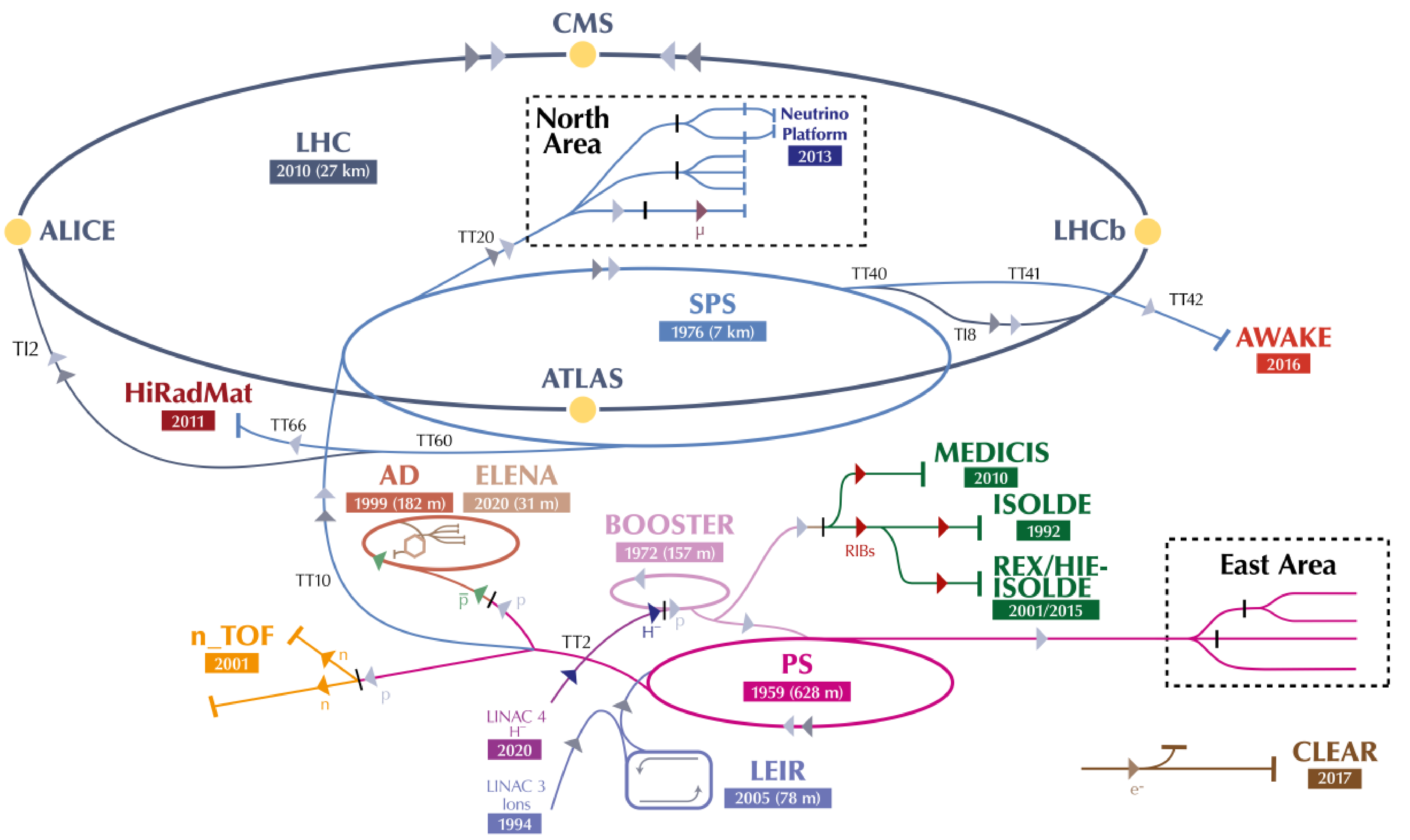

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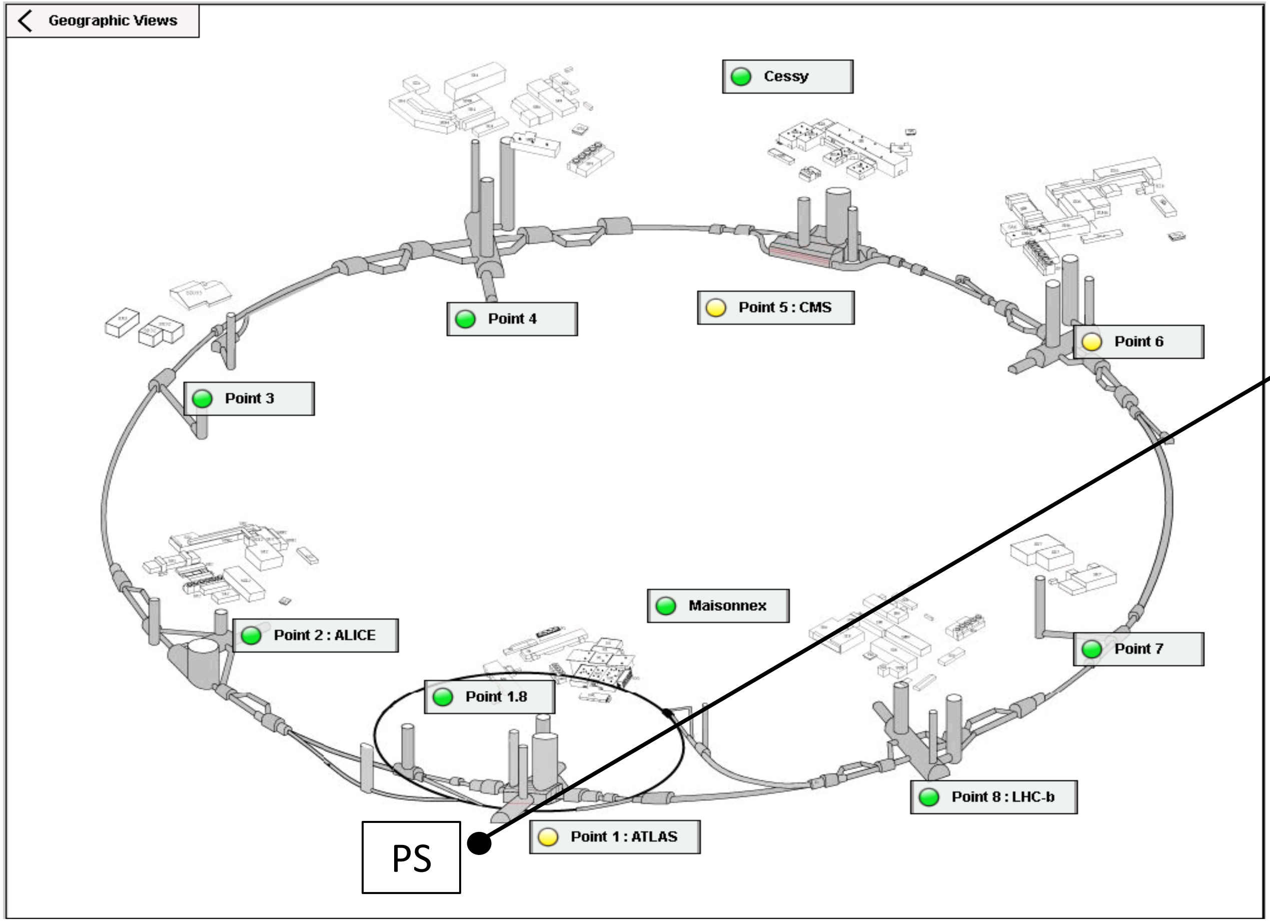
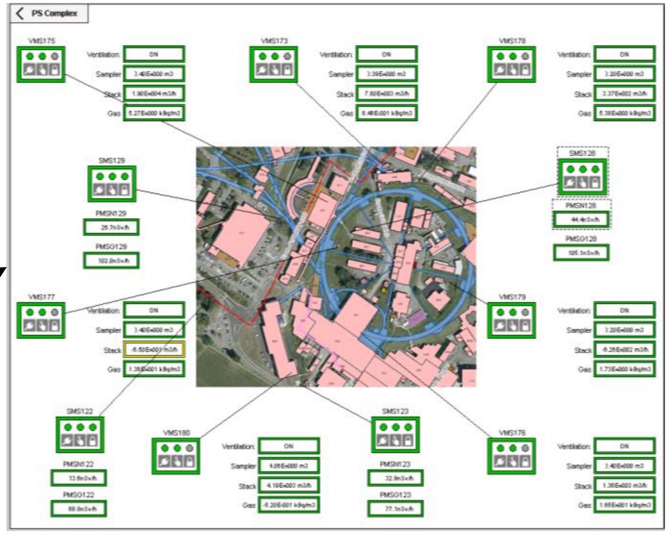
REMUS: CERN **R**adiation and **E**nvironment **M**onitoring **U**nified **S**upervision





In 2019:
3211 Measurement channels:
- 864 RP main channels + 1824 auxiliary
- 523 Environmental channels

26 Types (categories) of monitoring stations
365 days/year, 24/7 operation

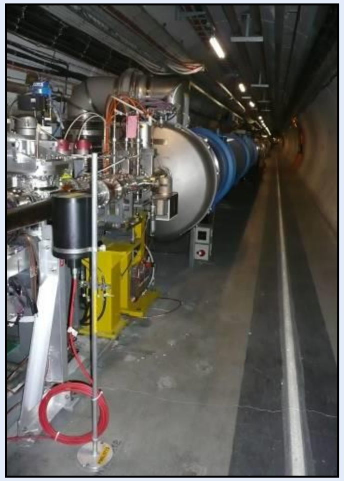
Radiation & Environmental Protection at CERN

REM counters

Gas filled, high pressure ionization chambers

Beam-on: to protect workers in areas adjacent to accelerator tunnels and experiments against prompt radiation (mainly neutrons, E < some GeV)

Alarm function



Air filled ionization chambers

Beam-off: to protect workers during maintenance and repair against radiation fields caused by decay of radionuclides (mainly gammas, E < 2.7 MeV)

No alarm function

Site Gate Monitors

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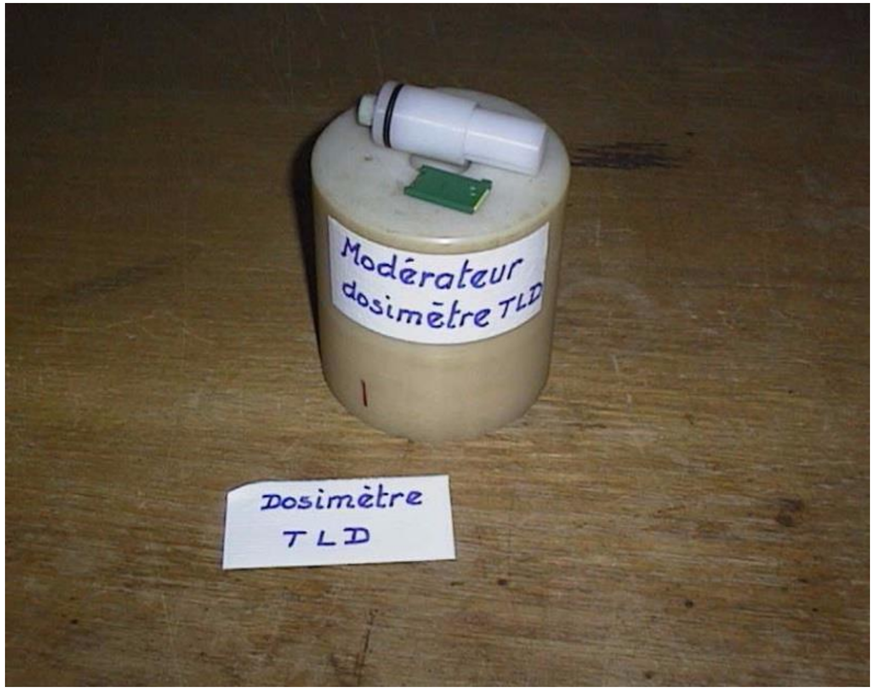
Thermoluminescence dosimeters (TLD) inside a polyethylene moderators are used to monitor neutron and gamma doses in the experimental areas and in the environment.



TLDs are passive devices used CERN-wide to integrate radiation doses over a period of several months.

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<table>
<tr><th></th><th>Supervised Area</th><th>Simple Controlled Area</th><th>Limited Stay Controlled Area</th><th>High Radiation Controlled Area</th><th>Prohibited Controlled Area</th></tr>
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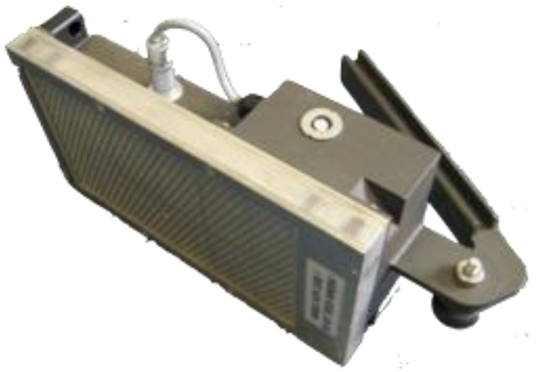
AUTOMESS dose rate meter 6150 AD6

AD17 external probe

<u>Detector:</u> Geiger Müller counter
<u>Range:</u> 0.5 µSv/h – 10 mSv/h
<u>Energy range:</u> 60 keV – 1.3 MeV
<u>Dimensions:</u> 130 mm x 80 mm x 29 mm
<u>Alimentation</u>: 9 V standard battery



ADK surface contamination meter for α, β and γ radiation
<u>Detector:</u> sealed proportional counter
Active surface 100 cm^2

POLIMI-CERN development of the B-RAD radiation survey meter

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First prototype

Five engineered units

Conceptual design

1st version

2nd version

Off-the-shelf product

The valley of death

COMMERCIAL VERSION OF THE B-RAD

- Developed for (also) operating in very intense magnetic fields (up to 3 T)
- Equipped with $LaBr_3$ crystal, 15 mm diameter x 15 mm height
- Energy resolution approximately 3% (^{137}Cs)
- User friendly, with double display (small with fast reading, big for detailed analysis)
- Leather bag for easy transport
- Radioisotope identification capability

A. Fazzi and M. Silari. Portable Radiation Detection Device for Operation in Intense Magnetic Fields. CERN/Politecnico joint patent. Patent Grant number 9977134 (2017)

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Thermal	< 0.1 eV (E_{th} = 0.025 eV)
Slow	< 0.5 eV (Cadmium cut-off energy)
Epithermal	0.1 – 10 eV
Intermediate	10 eV – 100 keV
Fast	100 keV – 100 MeV
High-energy	> 100 MeV

Some elements have a **very large** cross section for slow neutrons, which can be exploited for neutron detection

For information on interaction of neutrons with matter, click here

Main challenges for neutron instrumentation

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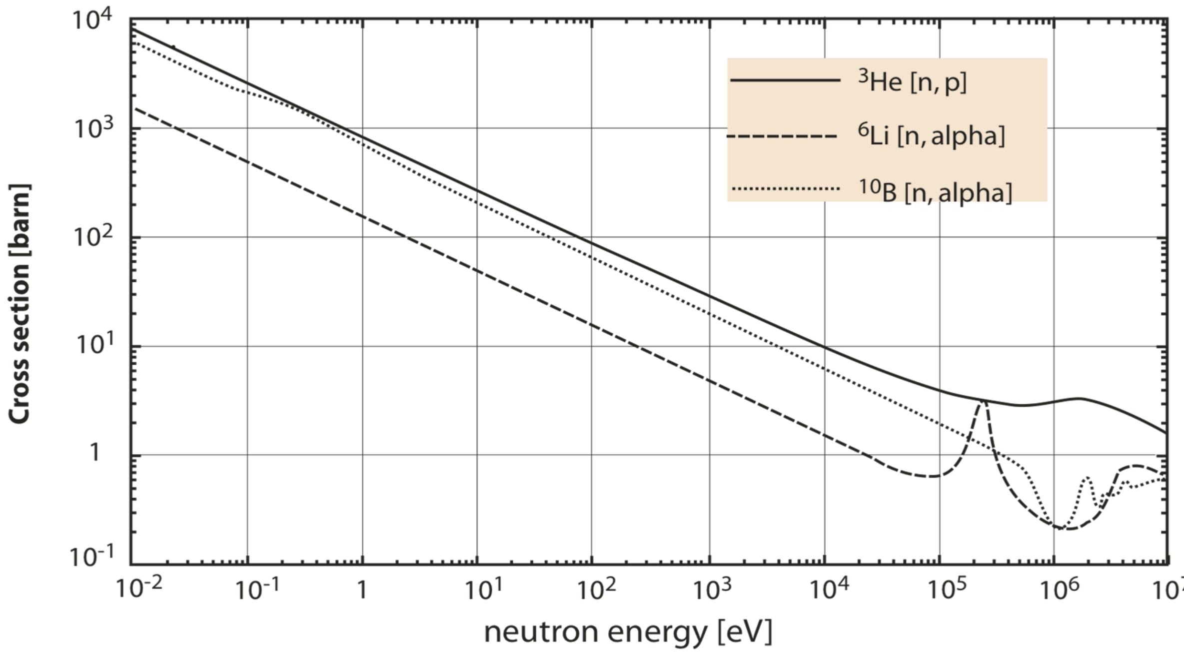
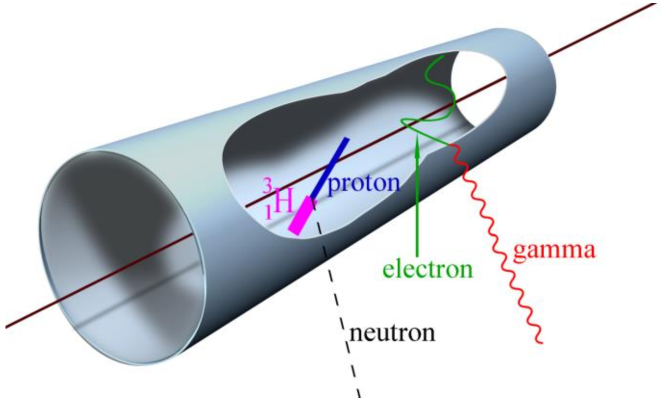
- Distinguish the various components (and their relative importance) of the mixed n/γ field
- Have a response function that approximately follows $H^*(10)$
- Measure correctly neutrons with E_n > 10 MeV (if present in the field)
- Sometimes operate in a (strongly) pulsed radiation field
- Measure ambient dose equivalent rates in the range from natural background (= a few hundreds of μSv per year) to a few mSv per hour

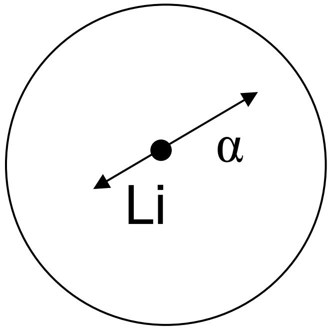
Thermal neutron detection reactions

Element	Nuclear rection	Thermal σ	Q
^{10}B	$^{10}B + n \rightarrow {}^{7}Li + \alpha$ $^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha$	3840 b	2.793 MeV 2.310 MeV
^{6}Li	$^{6}Li + n \rightarrow {}^{3}H + \alpha$	941 b	4.780 MeV
^{3}He	$^{3}He + n \rightarrow {}^{3}H + p$	5330 b	0.764 MeV

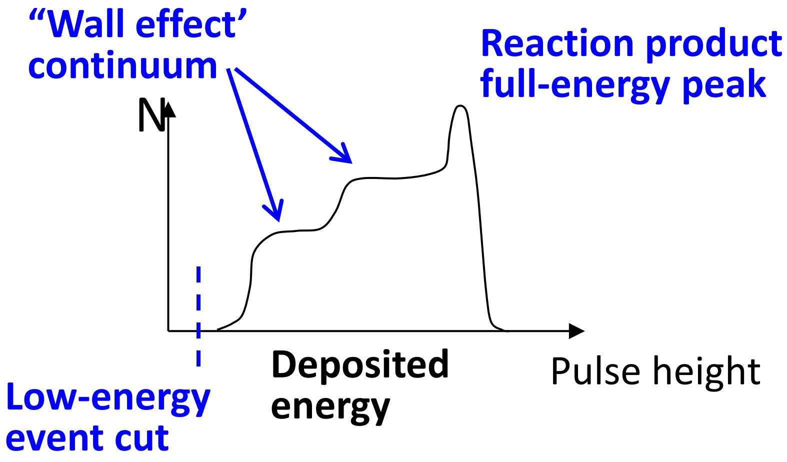
$$Q = (M_1 + M_2)c^2 - (M_3 - M_4)c^2$$







n/γ discrimination



^{3}H vs BF_3

Conventional and extended-range moderator-type neutron detectors

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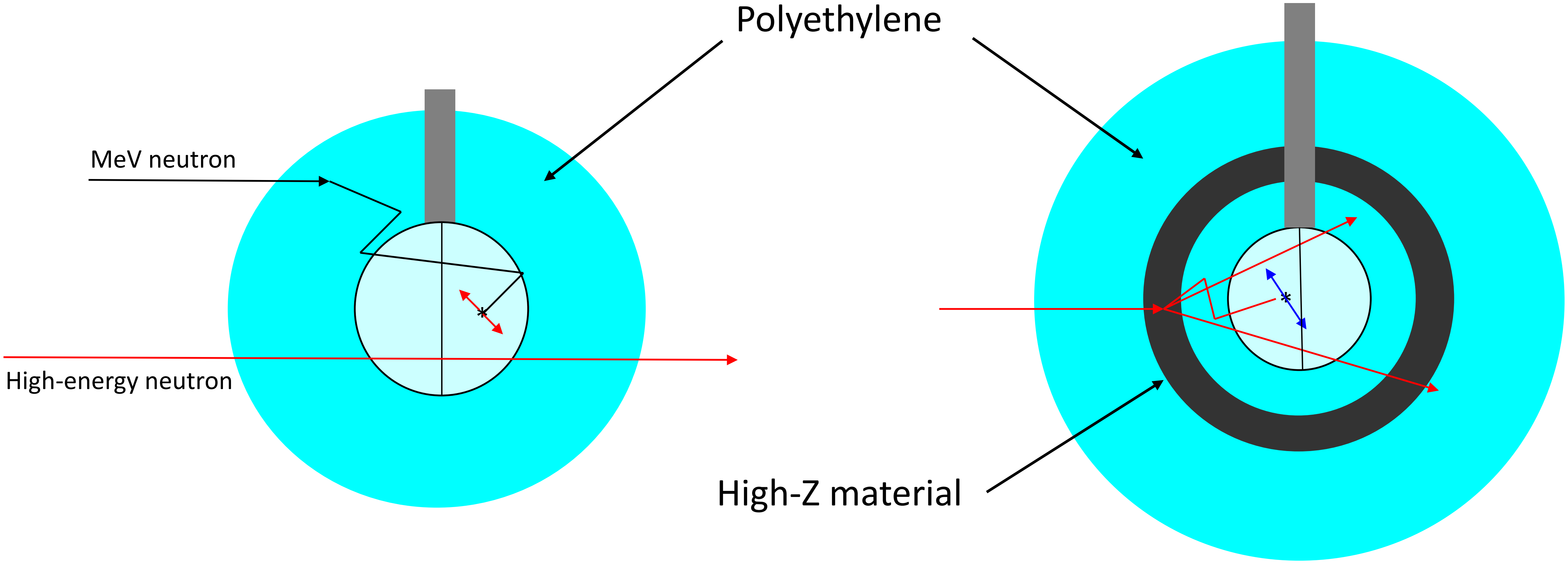

Conventional

Extended-range

(originally designed for use at nuclear power plants, max E_n 10-15 MeV)

Extended-range rem counter LINUS

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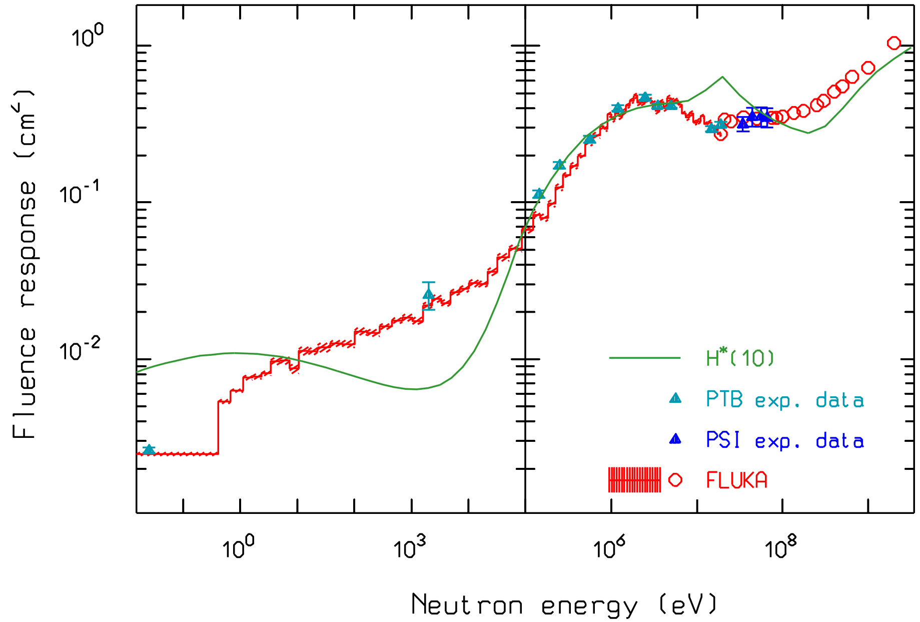
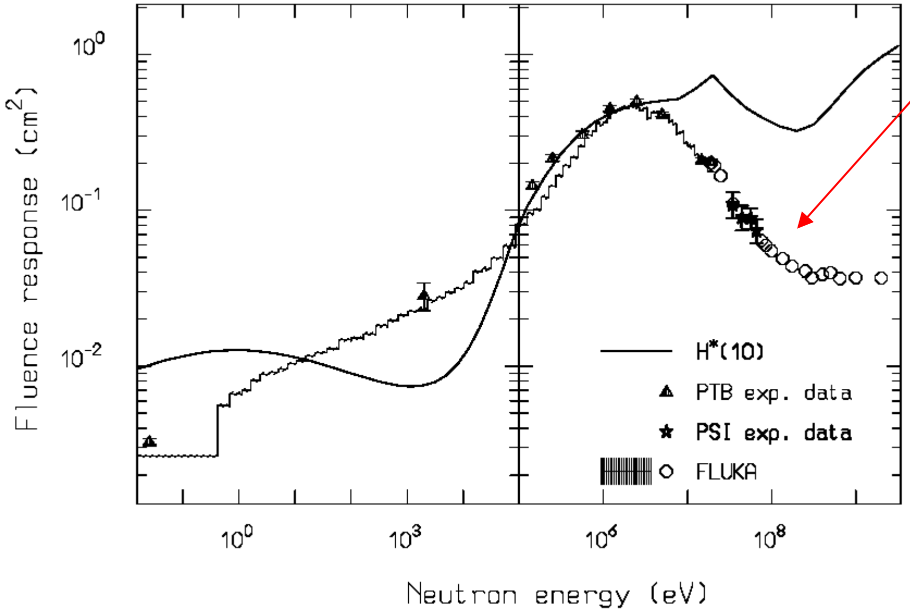
LINUS (extended range)



SNOOPY (conventional)



Large underestimation above a few MeV

$$M = C \int R_{\Phi}(E)\, \Phi(E)\, dE$$

C. Birattari, A. Esposito, A. Ferrari, M. Pelliccioni, M. Silari, NIM A324 (1993) 232-238

C. Birattari, A. Esposito, A. Ferrari, M. Pelliccioni, T. Rancati, M. Silari, RPD 76 (1998) 135-148

Commercial rem counters

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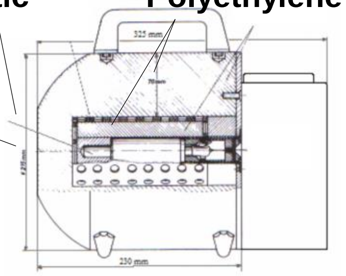
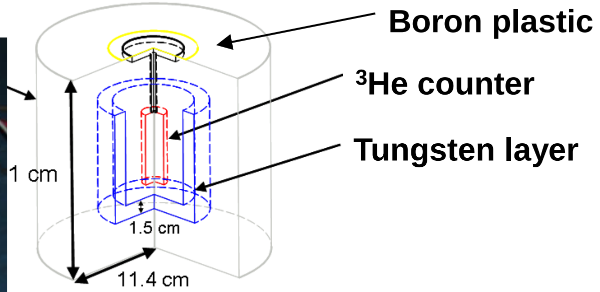
ELSE NUCLEAR LUPIN 5401 Series

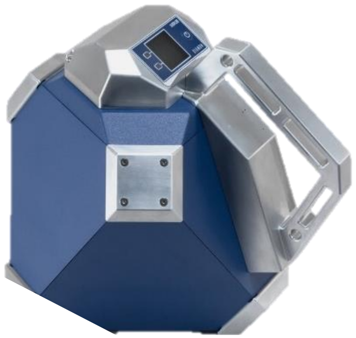
Studsvik 2202D



Fuji Electric NSN10014

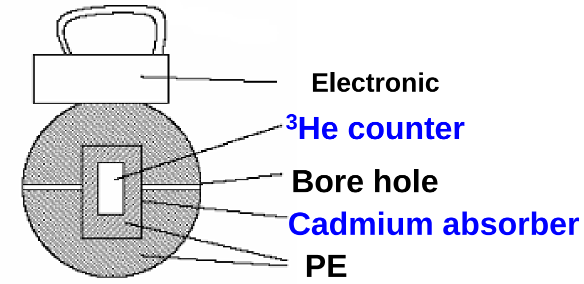


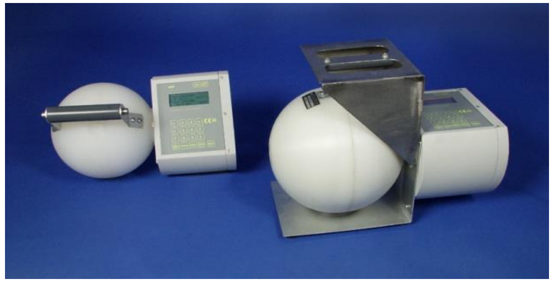
Eberline WENDI-2



RayLab DIAMON

Berthold LB6411 (also LB6411Pb)





MAB SNM500(X)

Passive rem counter – POLIMI passive LINUS

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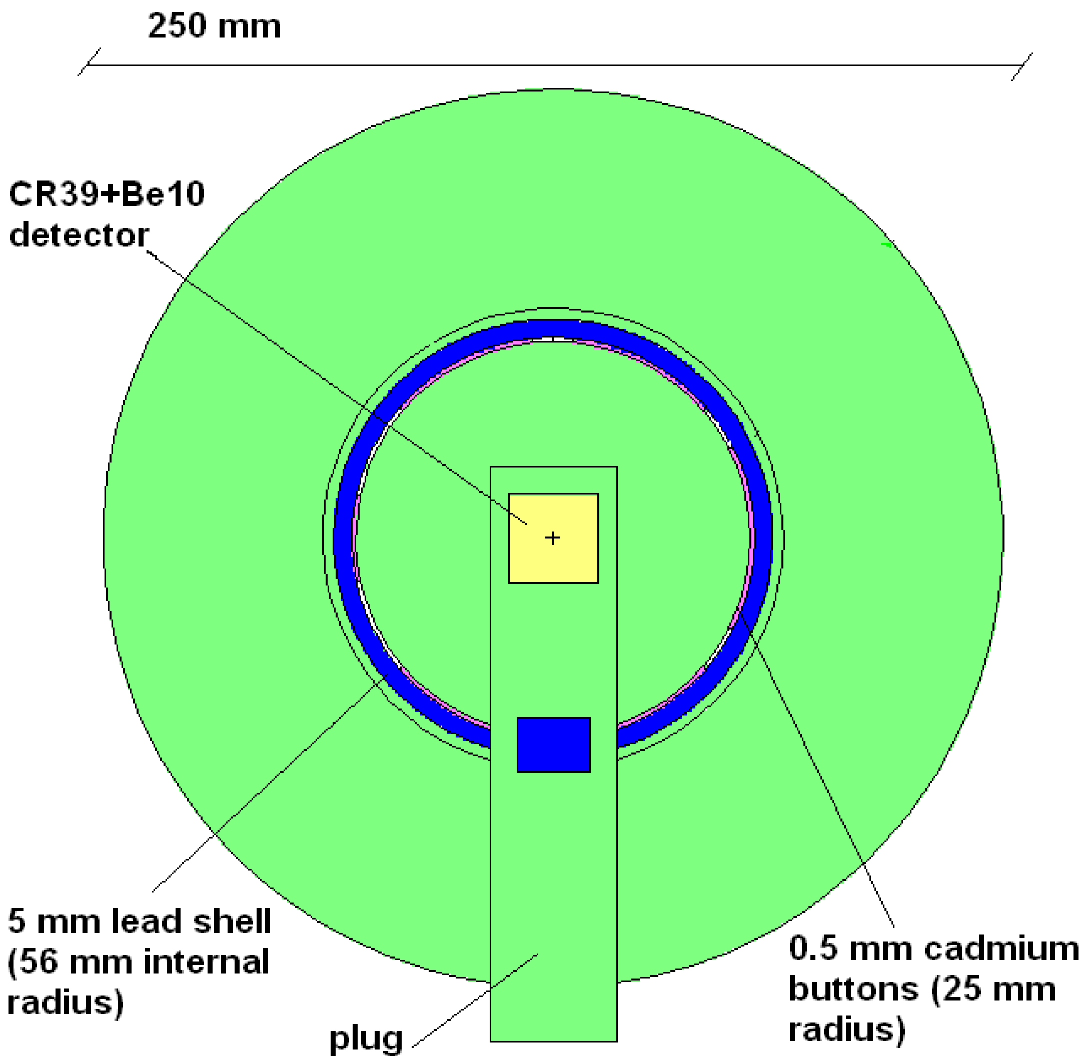
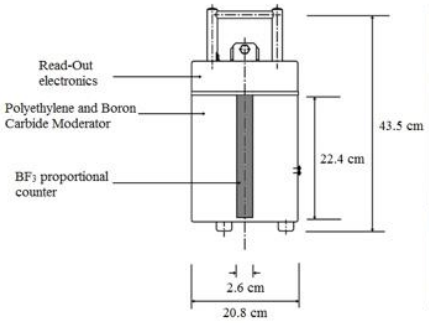


Courtesy M. Caresana, Politecnico of Milano

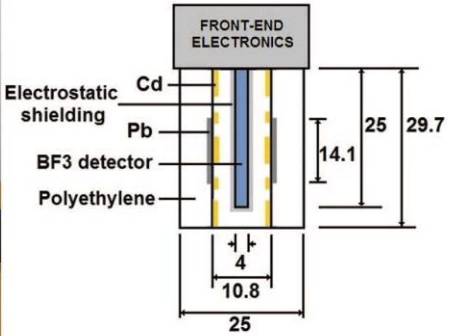
For more information on track analysis, click here

In summary: four “classes” of rem counters

- **Conventional rem counter**
  BIOREM (good sensitivity up to 20 MeV)

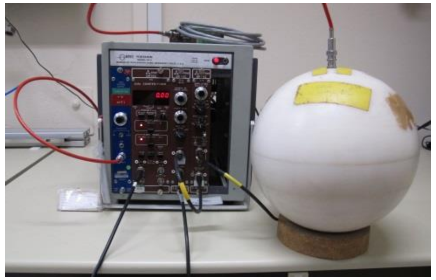


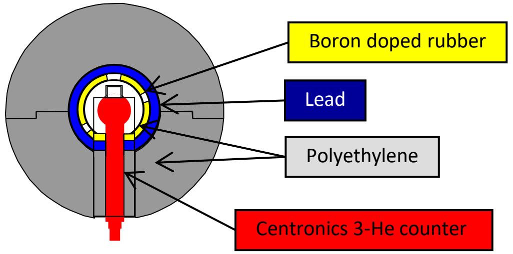
- **Rem counter for pulsed fields**
  LUPIN, BF_3 version



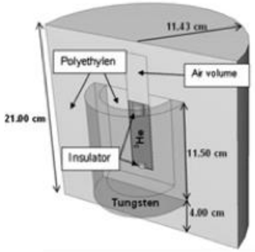
- **Extended-range rem counters**
  (good sensitivity up to 5 GeV)

LINUS





WENDI II



- **Passive rem counters**
  (requires off-line analysis)

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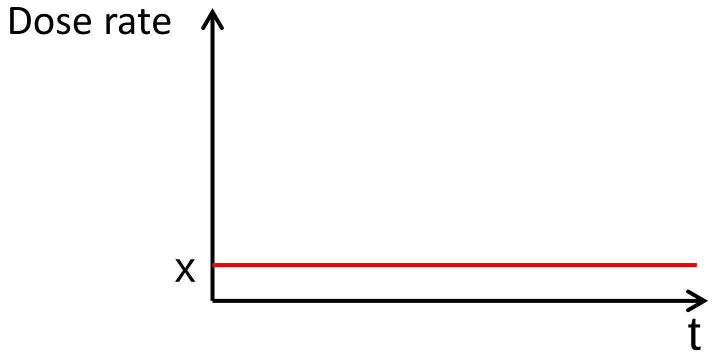
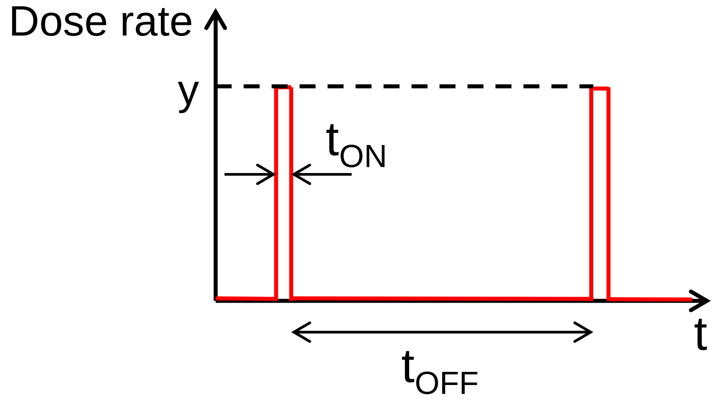
Radiation field

STEADY



PULSED



Same **averaged** dose rate but different **instantaneous** dose rates

$$x = y \frac{t_{ON}}{t_{ON} + t_{OFF}}$$

DUTY FACTOR

Small DUTY FACTORS (=> high instantaneous dose rates) impose severe limitations on the survey meters to be employed

For more information on detector dead time, click here

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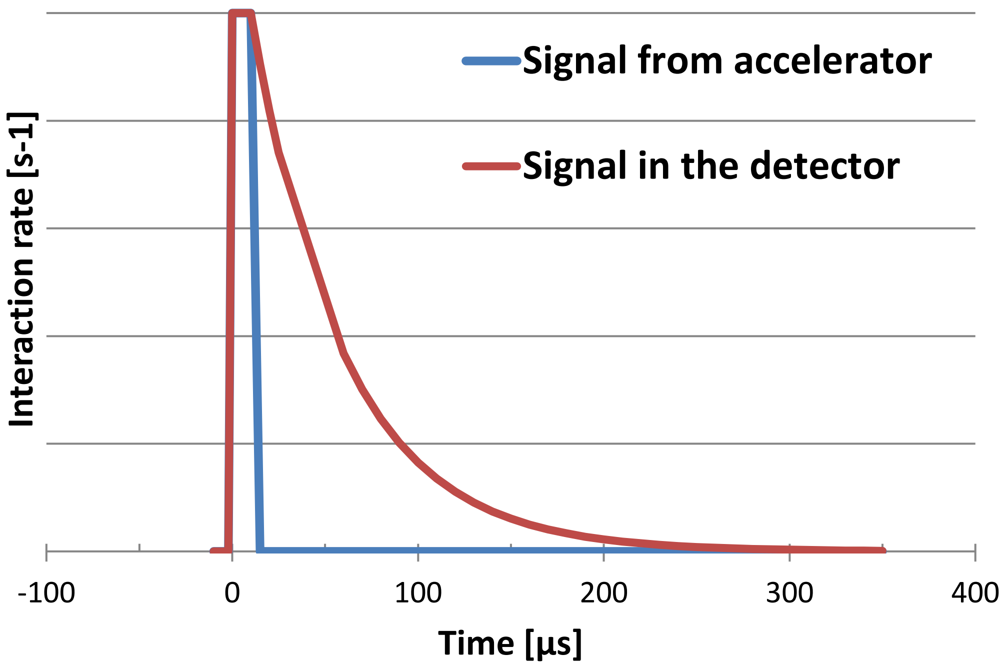
Performances of detectors (rem counters) in pulsed neutron fields:

- **Dead time effects (↓)**
- **Neutrons thermalization and diffusion time (TDT) in the moderator (↑)**



Signal in the detector spread over several hundred μs, regardless of the original pulse width

↓

REDUCED UNDERESTIMATION

For more information on neutron diffusion and thermalisation, click here

LUPIN: **L**ong interval, **U**ltra-wide dynamic, **PI**le-up free, **N**eutron rem counter

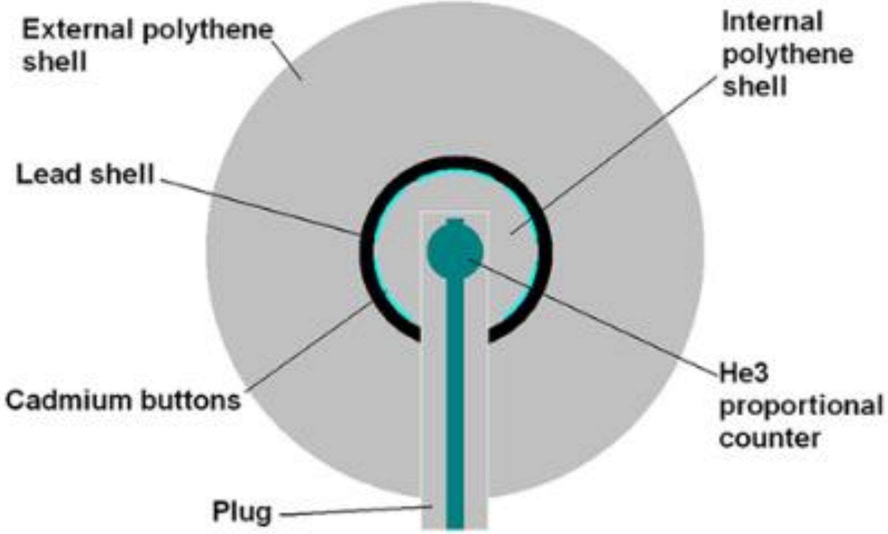
Proportional counter
^{3}He or BF_3

+

Moderator
(response function reproduces the curve of the **neutron fluence to H*(10)** conversion coefficients)

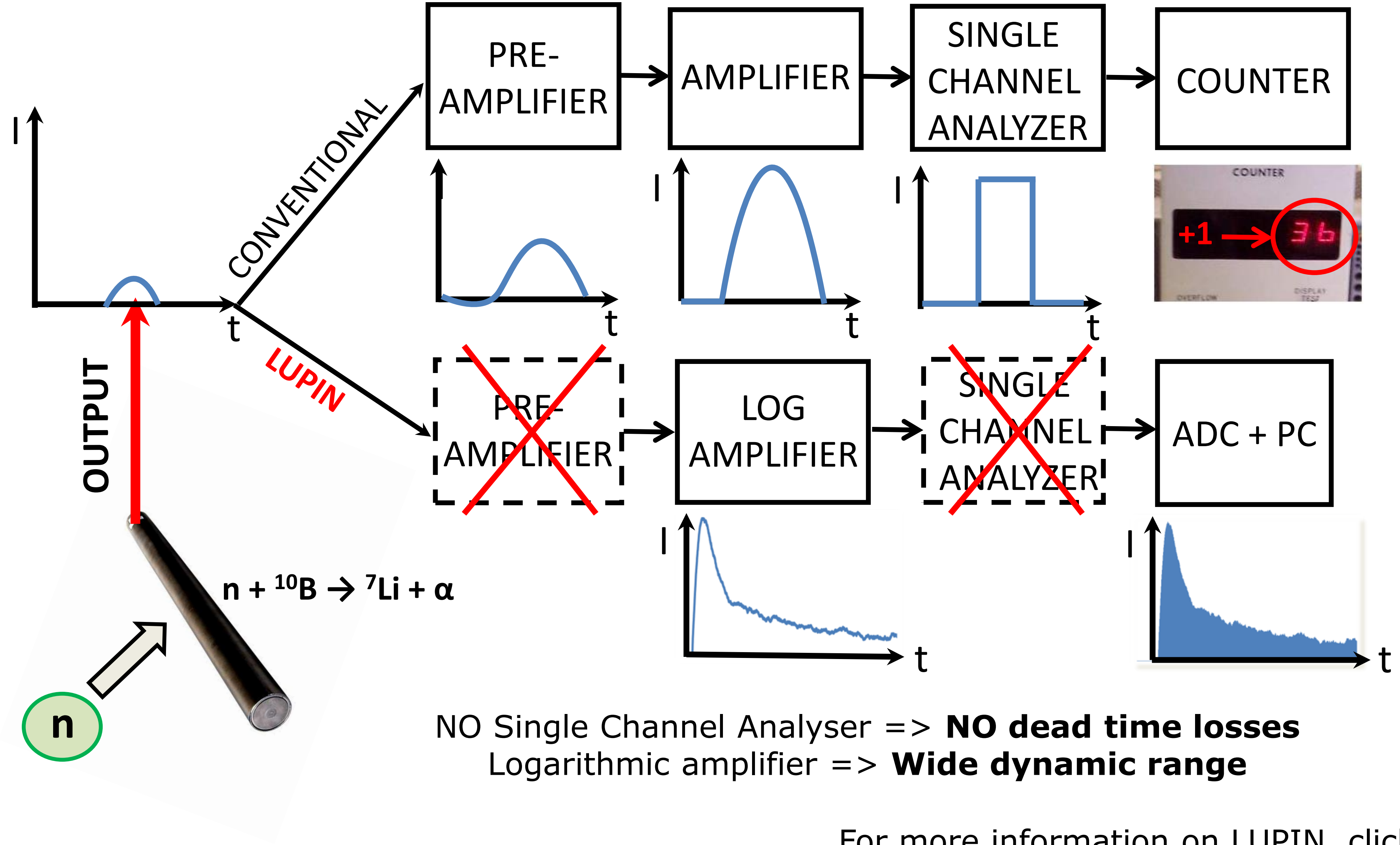
+

Innovative front end electronics



M. Caresana, M. Ferrarini, G.P. Manessi, M. Silari, V. Varoli, LUPIN, a new instrument for pulsed neutron fields, Nuclear Instruments and Methods A 712 (2013) 15-26

LUPIN operating principle



NO Single Channel Analyser => **NO dead time losses**
Logarithmic amplifier => **Wide dynamic range**

For more information on LUPIN, click here

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- **Wearing a personal dosimeter** on the chest or at the waist
  - monthly measurement (at least)
  - Information may be delayed (depends on dosimeter)
  - measurement threshold ~0.1 mSv/month
- **Wearing an electronic dosimeter**
  - instantaneous information
  - possibility to setting a dose or dose rate alarm
- **Wearing an extremity dosimeter**
  - In the case of specific hand exposure risk (handling of radioactive substances)

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- **The dosimeter is calibrated to measure:**
  - **$H_p(10)$:** personal equivalent dose at a depth of 10 mm in the chest
  - **$H_p(0.07)$:** personal equivalent dose at a depth of 0.07 mm in the chest
- **At low measured doses** (less than the limits) it is assumed that:
  - the effective dose and the equivalent dose to each organ is equal to $H_p(10)$;
  - the equivalent dose to the skin is equal to $H_p(0.07)$;
- **At high measured doses** (exceeding the limits),
  - an investigation is undertaken (**dosimetric reconstruction**) to determine the effective dose and the equivalent doses to the organs which were actually received.

Personal dosimetry for monitoring external exposure

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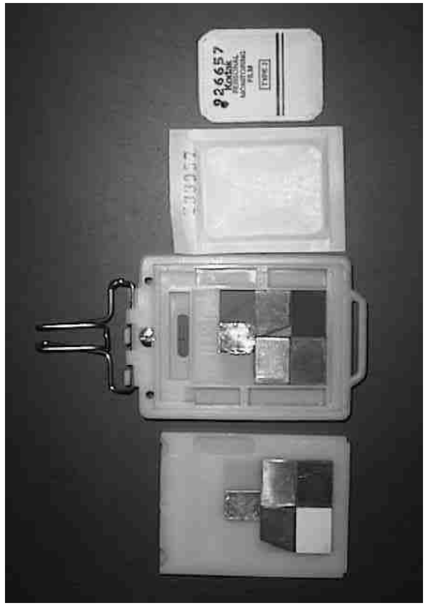
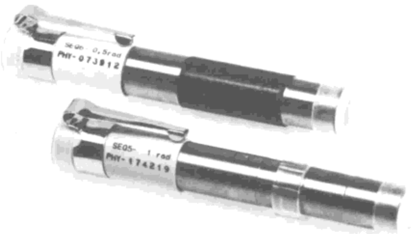


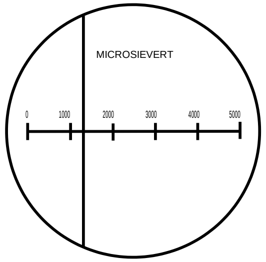
Kodak film badge

Personal dosimeter: "Legal dose”

RADOS DIS

Finger dosimeter





Quartz-fiber dosimeter (ionisation chamber and electroscope)

Operational dosimeter DMC: “Operational dose”

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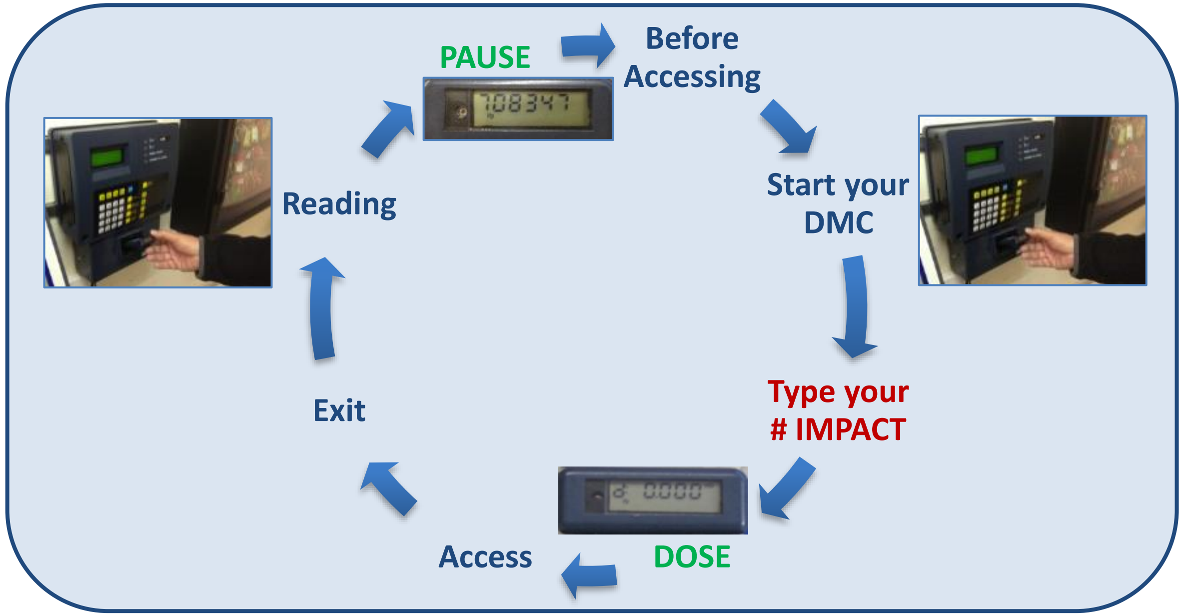
- Continuous measurement of $\beta\gamma$-dose (DIS-system) and integration of the neutron dose (track dosimeter)
- Obligation to wear the dosimeter in supervised and controlled areas
- Wearing of the dosimeter on the chest
- Reading at least once a month at a reader (about 50 readers available on the site)
- Possibility of checking the dose associated with a given operation (read the dosimeter before and after)
- Dosimeter to be returned to the dosimetry service at the end of stay or at the end of a 12-month period

- Obligation to wear an operational dosimeter in a controlled area
- Continuous βγ-dose measurement
- Instrument: DMC
- Display of Hp(10) (resolution of 1 μSv)
- Dose alarm at 2 mSv
- Dose rate alarm at 2 mSv/h
- Audible detection signal (« bip »)

- Record the dose before and after an intervention



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Radioactive contamination at particle accelerators can arise from:

- the use of unsealed radioactive sources
- activation of air and dust around the accelerators
- activation of oils or cooling fluids
- the machining or treatment of radioactive components
- normal or accidental emissions from targets whilst they are irradiated or after irradiation

Two factors should be considered in defining precautions for the control of unsealed radioactivity:

- the prevention of the contamination of
  - personnel
  - equipment

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- Material that has been brought into and removed from an accelerator tunnel or bunker during shutdown (maintenance) will no be activated

  BUT …

  … it might be contaminated

- If there is a suspicion of contamination, it must be checked before leaving the area

Personal protection equipment against contamination

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Individual protection equipment is mandatory for work in areas with contamination risk (cleaning operations, machining of radioactive material or equipment, …)

For more information on PPE, click here

Contamination monitors

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APA

CMS2000

Air contamination monitors

Hand and foot monitor

ABPM203M

- Induced radioactivity depends on many factors:
  - type and energy of accelerated particles, beam intensity, materials irradiated by the primary beam and secondary radiation

- Induced radioactivity has consequences for:
  - the exposure of personnel during maintenance
  - the maintenance of accelerator components, in particular the control of the spread of contamination during machining of radioactive components
  - the administrative control of movement of radioactive items
  - the disposal of radioactive waste

- All particle accelerators with E > 10 MeV will produce some induced radioactivity, but certain nuclear reactions with light target nuclei produce neutrons (and hence radioactivity) at energies well below 10 MeV

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For a given particle, target element and nuclide, the nuclide production rate is determined by:

- Interaction probability, σ (*cross section*)
- Flux (spectrum), Φ
- Beam intensity, I_p

$$n = I_p \frac{\rho N_{Av}}{A} \sum_{i=p,n,\pi,pho} \int \Phi_i(E) \sigma_i(E)\, dE$$

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- Although the number of radionuclides that might be produced is very large, the number of concern in radiation protection is limited by a combination of production cross-section and radioactive half-life
- The law of radioactive build-up and decay is:

$$A = A_s (1 - e^{-t_{irr}/\tau}) e^{-t_{dec}/\tau}$$

- Several hours after irradiation, radionuclides with very short half-lives have decayed, while those with very long half-lives are both produced and decay very slowly
- Induced activity produced by high-energy proton accelerators is ~ 100 times than that produced by high-energy electron accelerators, for the same beam power

For more information on induced radioactivity, click here

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- Surface Contamination < 1 CS
- Dose Rate < 0.1 μSv/h (10 cm distance)
- **Mass Specific Activity < 1 LE**

For a mixture of radionuclides (as is often the case):

$$R = \sum_i {}^{a_i}/_{LE(swiss)_i} < 1$$

Methodology

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1. **Recovery of background information**
   - **Description:** Material type, material composition, size, weights
   - **Location** (tunnel, experimental areas)
   - **Primary particle** (electrons, protons, etc.) **and energy** (tens of MeV to 7 TeV)
   - **Irradiation** and **cooling times**
2. **Theoretical activation study**
   - **Monte-Carlo simulations:** to obtain particle fluence spectra
   - **Radionuclide inventory** calculated using the CERN ActiWiz software
3. **Experimental study**
   - Extensive **sampling**: γ-spectrometry measurements, radiochemical analysis
   - **Dose rate** and **contamination** measurements
4. **Documentation** for **project proposal** to Swiss authorities: *detailed report on experimental and computational studies, operational procedure, protocol of clearance measurements, safety files, …*
5. **Operational phase**: **worksite** management, contact with **scrap dealers**, **elimination** of the material, etc.

For information on project CLEAR, click here

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Operational phase - workflow

Storage area in ISR7

Transportation to ISR4

Storage area in ISR4

Working area in ISR4

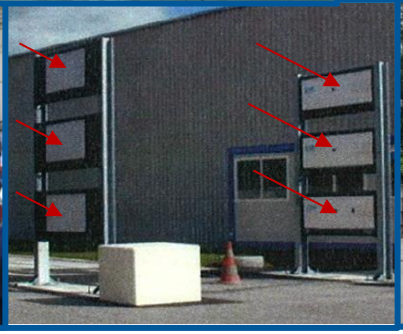
Contamination
Dose rate

Sampling
γ-spectrometry

Spectrometry of the other components

Buffer zone in ISR4 (temporary storage)

After OFSP approval, transportation to the French CERN site for control



Gate monitor control with 6 large area detectors

Storage for sale to Swiss scrap dealers

A positive impact on society

Amount of rock m_{rock} that would have to be excavated to extract the same mass of metals m_{metals} recycled by CERN radiological clearance projects *CLEAR, ELISA, CLELIA, AMELIA* and *AMAL* from 2016 to July 2022 using ore grade - the share of ore that is useable metal.

Element	Ore grade [%]	m_{metals} [tons]	m_{rock} [tons]
Aluminium	19.0	261	1 636
Copper	0.9	104	11 615
Iron	40.0	804	2 815
Lead	60.0	72	191
Nickel	0.5	7	1 407
TOTAL		1 238	16 415

Some references - Dosimetry and instrumentation

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Glenn F. Knoll, Radiation Detection and Measurement, John Wiley & Sons, Inc., 4th edition

Frank H. Attix, Introduction to Radiological Physics and Radiation Dosimetry

Annals of the ICRP (International Commission on Radiological Protection)
http://www.icrp.org/publications.asp

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http://www.icru.org/

Original Andersson-Braun paper:

- I.O. Andersson and J.A. Braun, Neutron Rem Counter with Uniform Sensitivity from 0.025 eV to 10 MeV. In: Proc. IAEA Symposium on Neutron Dosimetry (Vienna: IAEA) Vol. II, 87–95 (1963)

Original work on extended-range rem counter LINUS:

- C. Birattari, A. Ferrari, C. Nuccetelli, M. Pelliccioni and M. Silari, An extended range neutron rem counter, Nuclear Instruments and Methods in Physics Research A297, 250-257 (1990)
- C. Birattari, A. Esposito, A. Ferrari, M. Pelliccioni, T. Rancati, M. Silari, The extended range neutron rem counter 'LINUS': overview and latest developments, Radiation Protection Dosimetry 76 (1998) 135-148

Rem counter for pulsed field (LUPIN):

- M. Caresana, M. Ferrarini, G. P. Manessi, M. Silari and V. Varoli, LUPIN, a new instrument for pulsed neutron fields, Nuclear Instruments and Methods A 712, 15-26 (2013)

Passive rem counter (Passive LINUS):

- S. Agosteo, M. Caresana, M. Ferrarini and M. Silari, A passive rem counter based on CR39 SSNTD coupled with a boron converter, Radiation Measurements 44, 985-987 (2009)

Some references - Induced radioactivity

M. Barbier, Induced radioactivity, North-Holland (1969)

R.H. Thomas and G.R. Stevenson, Radiological safety aspects of the operation of proton accelerators, IAEA Technical Report Series 283 (1988)

A.H. Sullivan, A guide to radiation and radioactivity levels near high energy particle accelerators, Nuclear Technology Publishing, 1992

Some references - Clearance (free release) of material in Switzerland

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C. Duchemin, M. Magistris, F. Pozzi, M. Silari, C. Theis, H. Vincke, Radiological clearance of equipment from high-energy electron accelerators: The example of LEP superconducting acceleration system, Nucl. Instrum. Methods Phys. Res. A 919 (2019) 42–55, http://dx.doi.org/10.1016/j.nima.2018.11.139.

L. Svihrova, K. Bauer, L. Bruno, G. Dumont, M. Magistris, N. Menaa, M. Silari, L. Ulrici, Radiological clearance of historical waste from particle accelerators, Nucl. Instrum. Methods Phys. Res. A 1065 (2024) 169476, https://doi.org/10.1016/j.nima.2024.169476

SUPPLEMENTARY MATERIAL

Prompt radiation at hadron accelerators

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Of the various particles generated by a target bombarded by a high-energy beam only neutrons, photons and muons can contribute significantly to the dose past a shield:

- ✓ protons and light fragments from evaporation are of low energy and are completely stopped in the air inside the accelerator or target hall (the range of a 5 MeV proton in air is 34 cm);
- ✓ pions decay with a very short half-life;
- ✓ high-energy hadrons interact with the shielding barrier and generate secondary radiation which should also be accounted for;
- ✓ the radiation field generated inside the barrier is composed of neutrons (mainly), protons, photons, electrons, positrons and pions.
- ✓ At energies > 10 GeV muons becomes important (and at ~ 100 GeV they can dominate some radiation environments)
- ✓ Muon shielding completely dominates the forward shielding requirements at very high energies (this is why very-high energy accelerators are installed underground)

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Interaction of neutrons with matter

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Scattering	Elastic (n,n)	E_n <10 MeV
	Inelastic (n,n’)	E_n >10 MeV
Absorption	Radiative (n,γ)	
	Non radiative (n,p) (n,α) (n,2n) …	
	Fission (n,f)	

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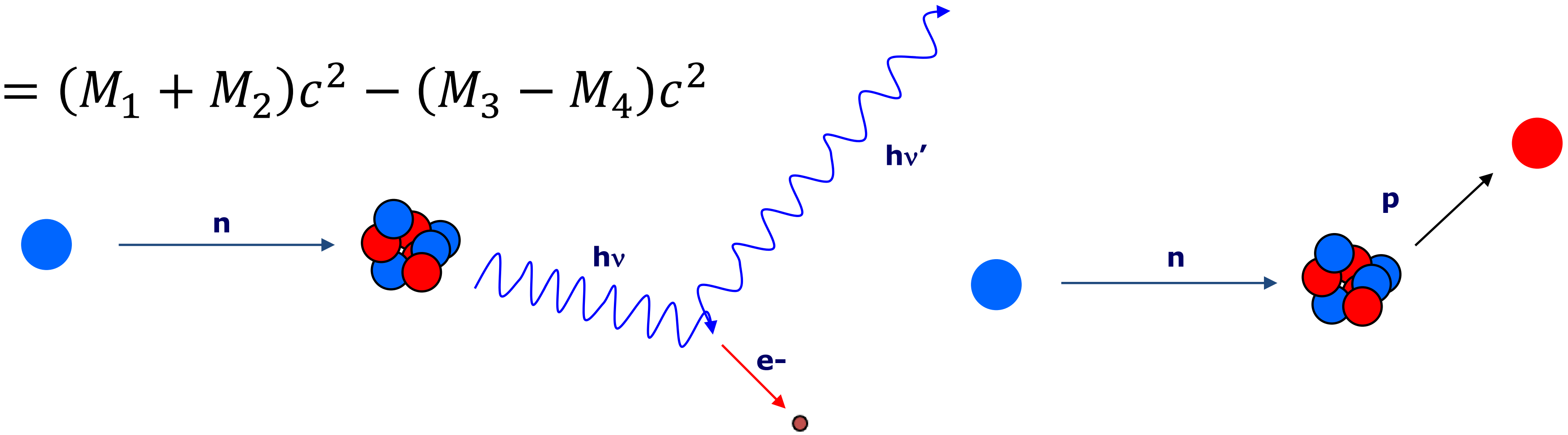
Element	Reaction	Q (MeV)	Cross section σ
H	$^{1}H(n,\gamma)^{2}H$	2.223	332 mb
C	$^{12}C(n,\gamma)^{13}C$	4.946	3.4 mb
N	$^{14}N(n,\gamma)^{15}N$	10.833	75 mb
N	$^{14}N(n,p)^{14}C$	0.626	1.81 b
O	$^{16}O(n,\gamma)^{17}O$	4.143	0.178 mb

Q-value: the amount of energy absorbed or released during the reaction

$$Q = (M_1 + M_2)c^2 - (M_3 - M_4)c^2$$



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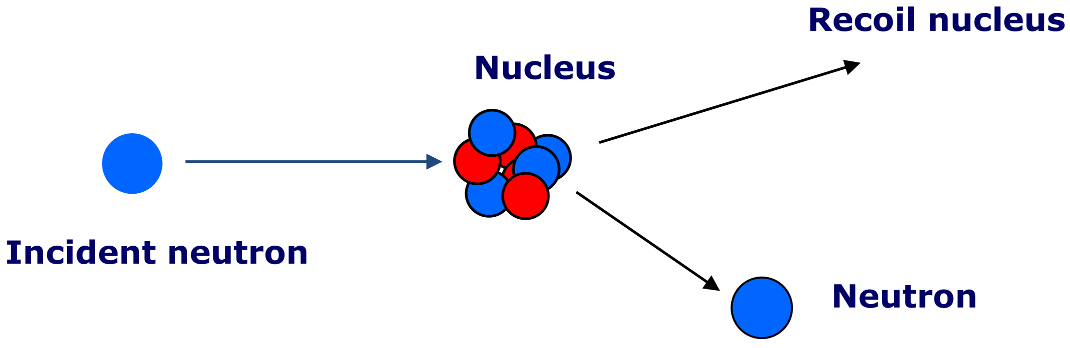
Elastic scattering (n,n) E_n <10 MeV

$$E_r = E_n \frac{4A}{(1+A)^2}(cos^2\theta)$$

Billiard ball - type collision

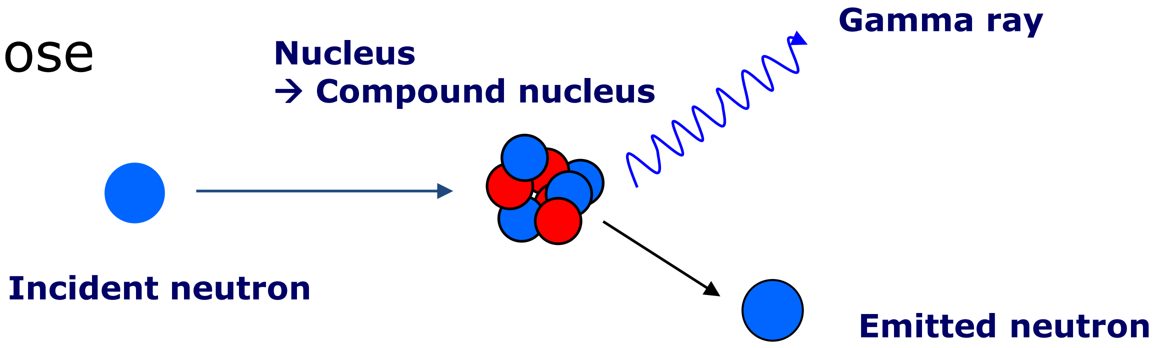


Target Nucleus	$E_{r,max}/E_n$
H	1
C	0.284
N	0.249
O	0.221

Elastic scattering is **not** effective to slow down high-energy neutrons

Recoil nuclei contribute to the absorbed dose

Inelastic scattering (n,n') E_n >10 MeV



Interaction of neutrons with matter

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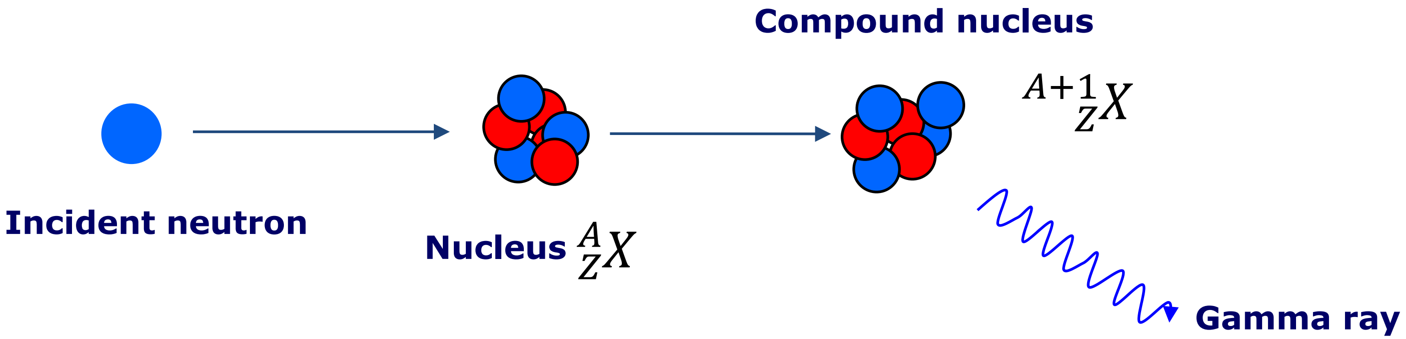
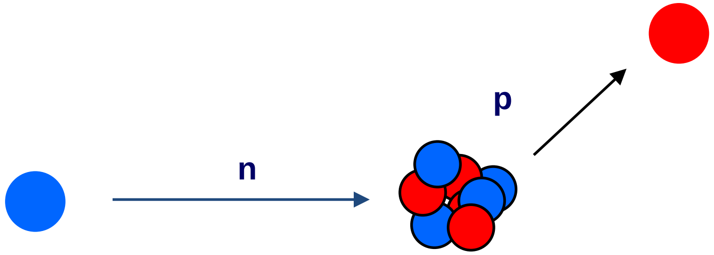
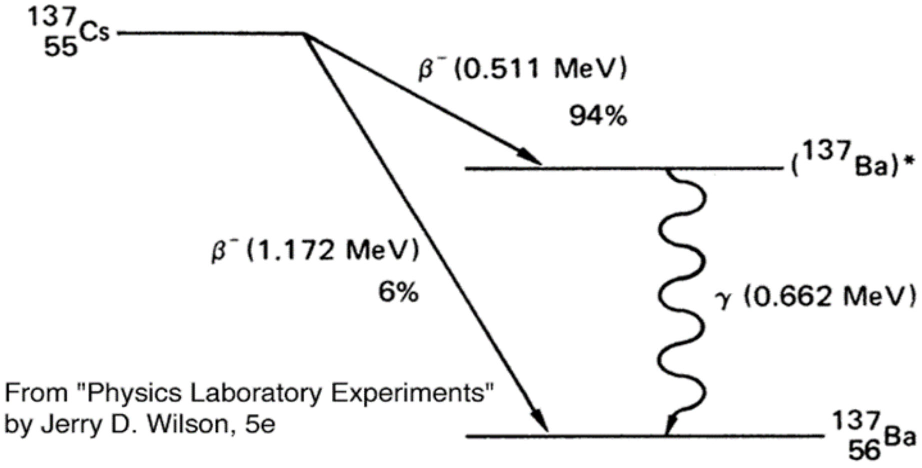
Radiative capture (n,γ)



Excitation energy 6-10 MeV (close to binding energy)
Decay time 10^{-16} s
Prompt γ-emission in 10^{-9} - 10^{-12} s

Non radiative (n,p) (n,α) (n,2n) …





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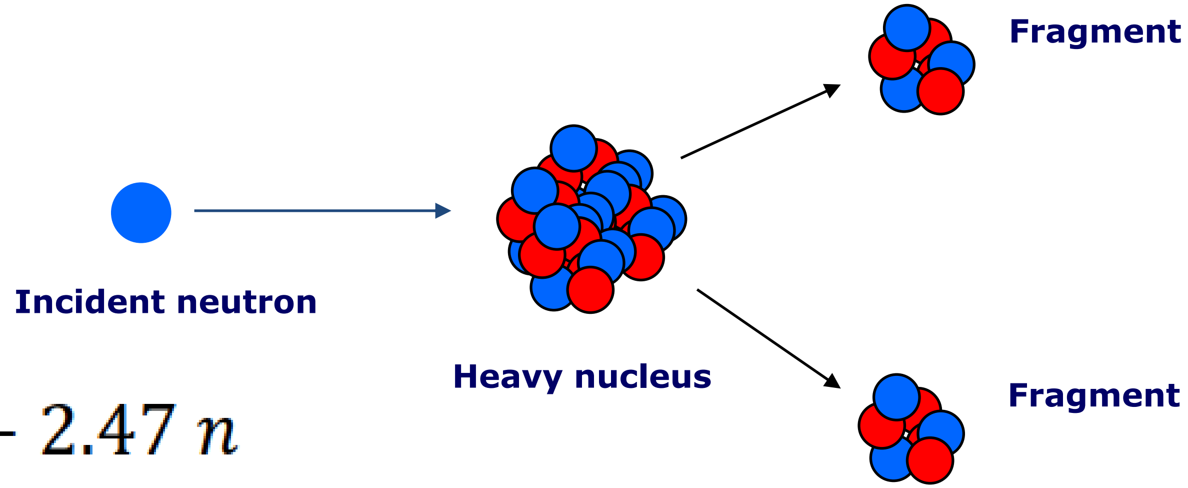
Fission (n,f)



$$^{235}_{92}U + \ ^{1}_{0}n \ \rightarrow F1 + F2 + 2.47\ n$$

Q = 207 MeV

Spallation reactions (n,xn)

Interaction of FAST neutrons with matter

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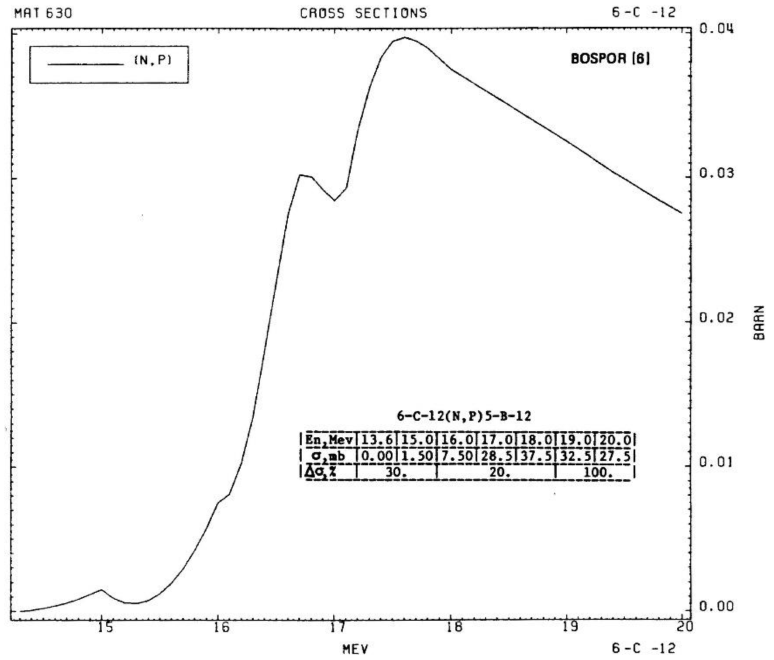
$$E_{th} = -Q\left(\frac{M_3 + M_4}{M_3 + M_4 - M_1}\right)$$

$$E_{th} = -Q\left(\frac{M_1 + M_2}{M_2}\right) \qquad M_2 \gg Q/c^2$$

Examples of inelastic reactions

Target Nucleus	Reaction	Q (MeV)	Threshold Energy (MeV)
C	$^{12}C(n,\alpha)^{9}Be$	-5.70122	6.18044
C	$^{12}C(n,p)^{12}B$	-12.58665	13.64462
C	$^{12}C(n,2n)^{11}C$	-18.72201	20.29569
N	$^{14}N(n,\alpha)^{11}B$	-0.15816	0.16955
N	$^{14}N(n,2n)^{13}N$	-10.55345	11.31363
O	$^{16}O(n,\alpha)^{13}C$	-2.21561	2.35534
O	$^{16}O(n,p)^{16}N$	-9.63815	10.24595
O	$^{16}O(n,2n)^{15}O$	-15.66384	16.65162



$^{12}C(n,p)^{12}B$

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BF_3 (cylindrical, 25 mm diameter x 150 mm length)

- Higher Q-value of the $^{10}B(n,\alpha)^{7}Li$ reaction w.r.t. the $^{3}He(n,p)^{3}H$ → better photon rejection
- Reduced space charge effects, due to the larger active volume w.r.t. ^{3}He
- But toxic and corrosive

^{3}He (spherical, 31 mm diameter)

- Isotropic response vs non-isotropic (±20% variation in the calibration factor for cylindrical BF_3 due to geometry)
- Higher sensitivity
- Harmless but expensive

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Passive rem counter – POLIMI passive LINUS

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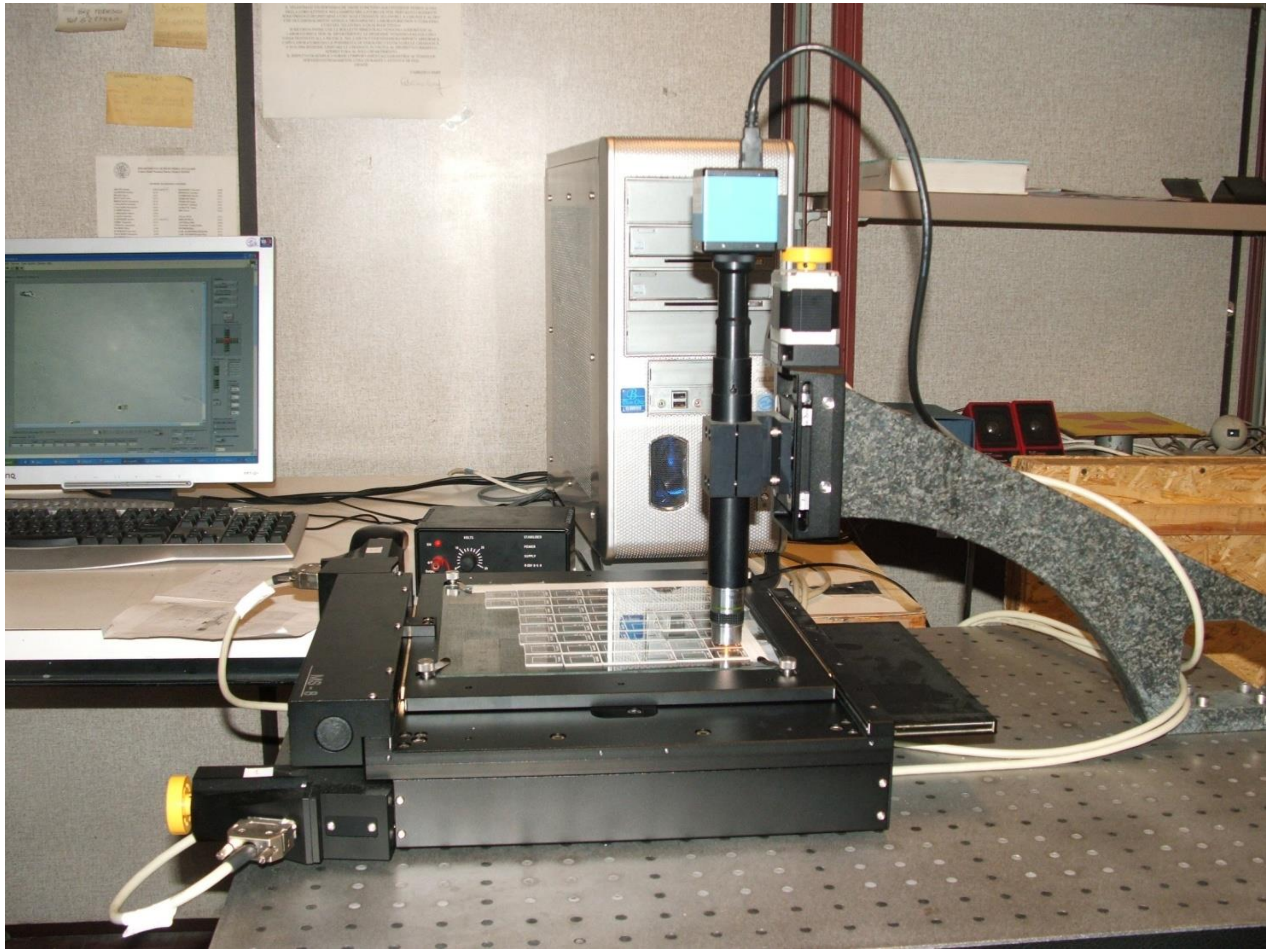

Trasmission microscope coupled with a 1024 x 768 CCD camera

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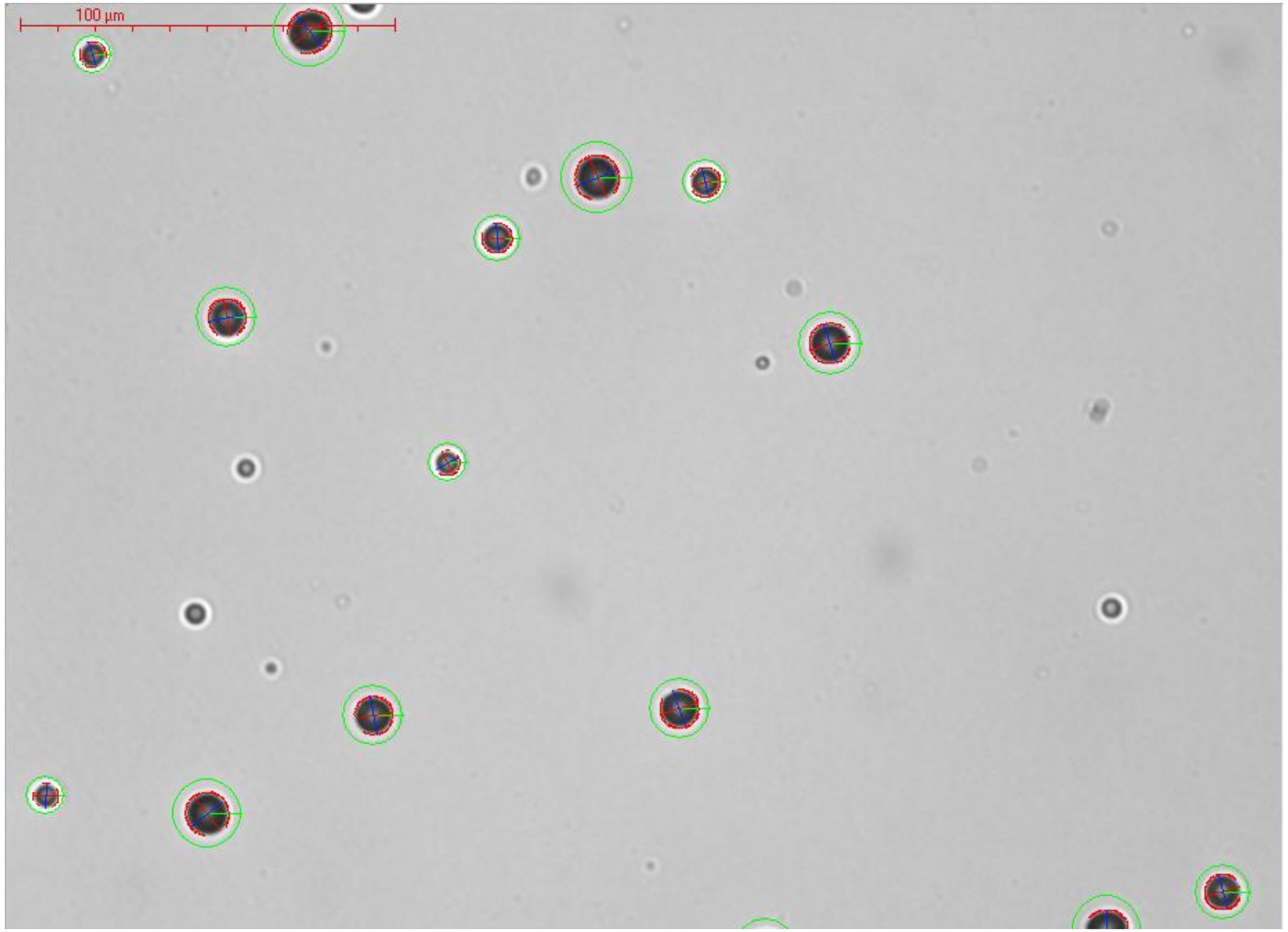

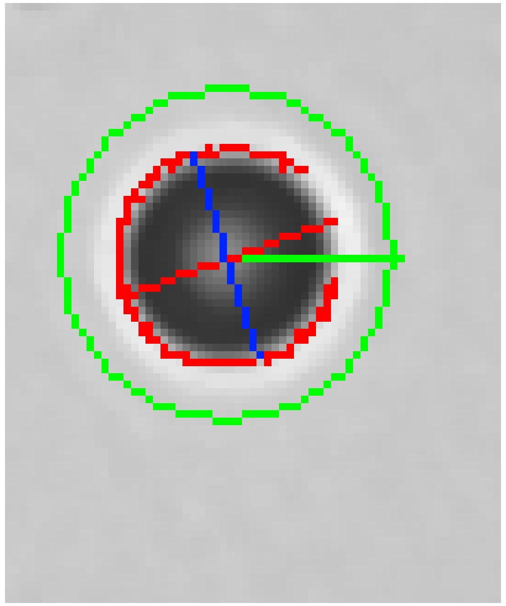

The Politrack software defines a ROI (green) inside which it searches the track boundary (red). Also, the track axis (red and blue) are drawn

Example of a frame obtained with the Politrack reader

Courtesy M. Caresana, Politecnico of Milano

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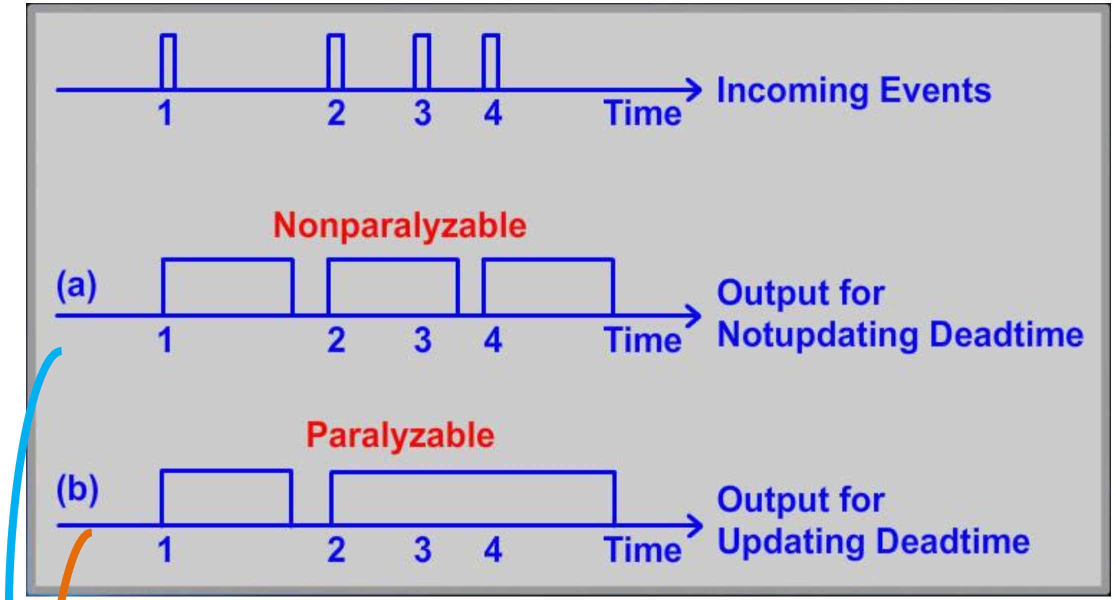

Fundamental property for a detector working in pulsed fields

Two response models

Typical values
GM: τ = 100 μs
Rem counter: τ = 1-10 μs

CORRECTION EQUATIONS
(**n**,**m** = true, measured interaction rate; τ = dead time):

$$n = \frac{m}{1 - m\tau}$$

$$n = m \cdot e^{-m\tau}$$

Detector dead time

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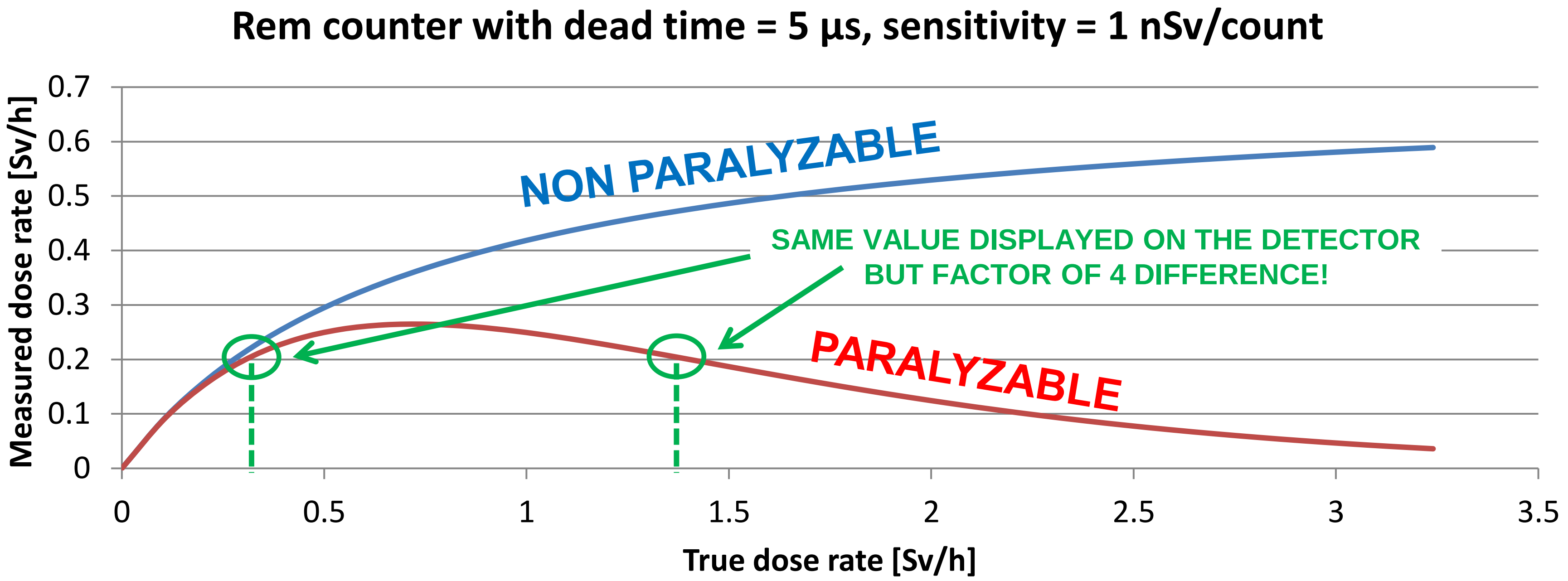

Correction equations work, but…

- Valid only for relatively low dead time losses
- Valid under the assumption that the interactions are uniformly distributed
  (=> This is not the case, by definition, for pulsed fields)

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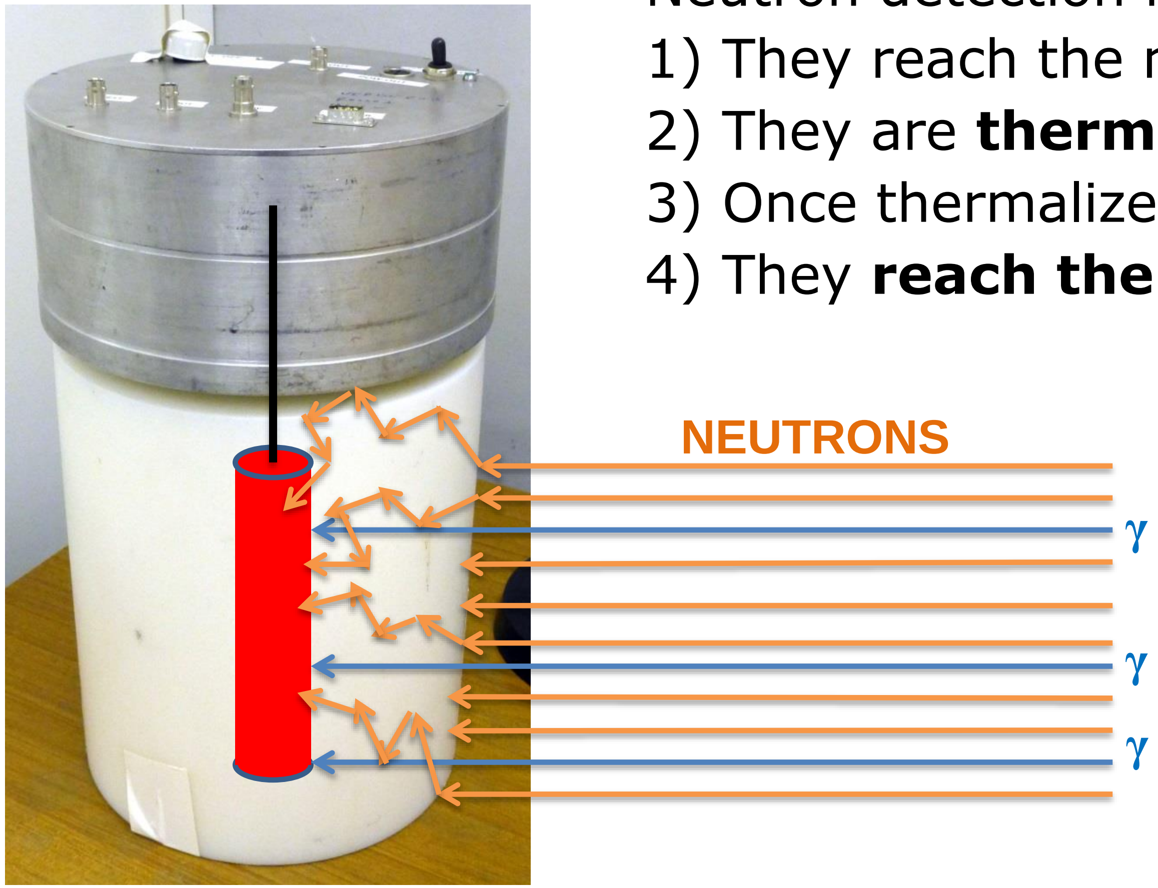
Detection of pulsed **neutron** fields shows an advantage, if compared to photons



Neutron detection mechanism:

1) They reach the moderator surface
2) They are **thermalized** (scattering events)
3) Once thermalized they **diffuse**
4) They **reach the detector** (BF_3 or ^3He)

Photons do not need thermalisation to be detected

N(t) = number of thermalized neutrons that reach the gas at time t:

$$N(t) = N_0 \cdot e^{-t/\tau'}$$

τ′ = decay constant of the neutrons in the moderator

(depends only on materials, size and shape of the moderator)

τ′ ≈ 140 μs for conventional spherical PE moderators (10-inch diameter sphere)

τ′ ≈ 70 μs for cylindrical PE moderators

enriched with Pb and Cd

(extended range detectors)

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LUPIN operating principle

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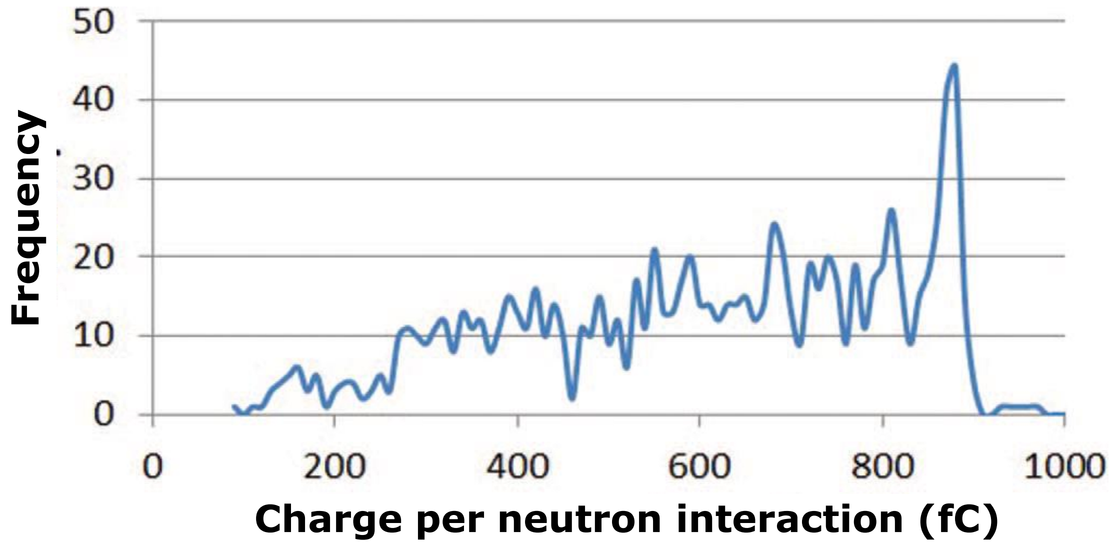
- Signal treated digitally; charge produced in the gas calculated by integrating the current over a settable time base
- Allows measuring the generated charge even if the neutron interactions pile up
- The total charge divided by the average charge expected by a single interaction represents the number of interactions occurring during the integration time
- Calibration of detector needs
  - knowledge of the mean collected charge (MCC) in fC, i.e., the average amount of charge generated in the detector by a neutron interaction
  - conversion coefficient from neutron interactions to H*(10), in nSv^{-1}



Example of signal acquired with LUPIN (CERN HiRadMat facility)

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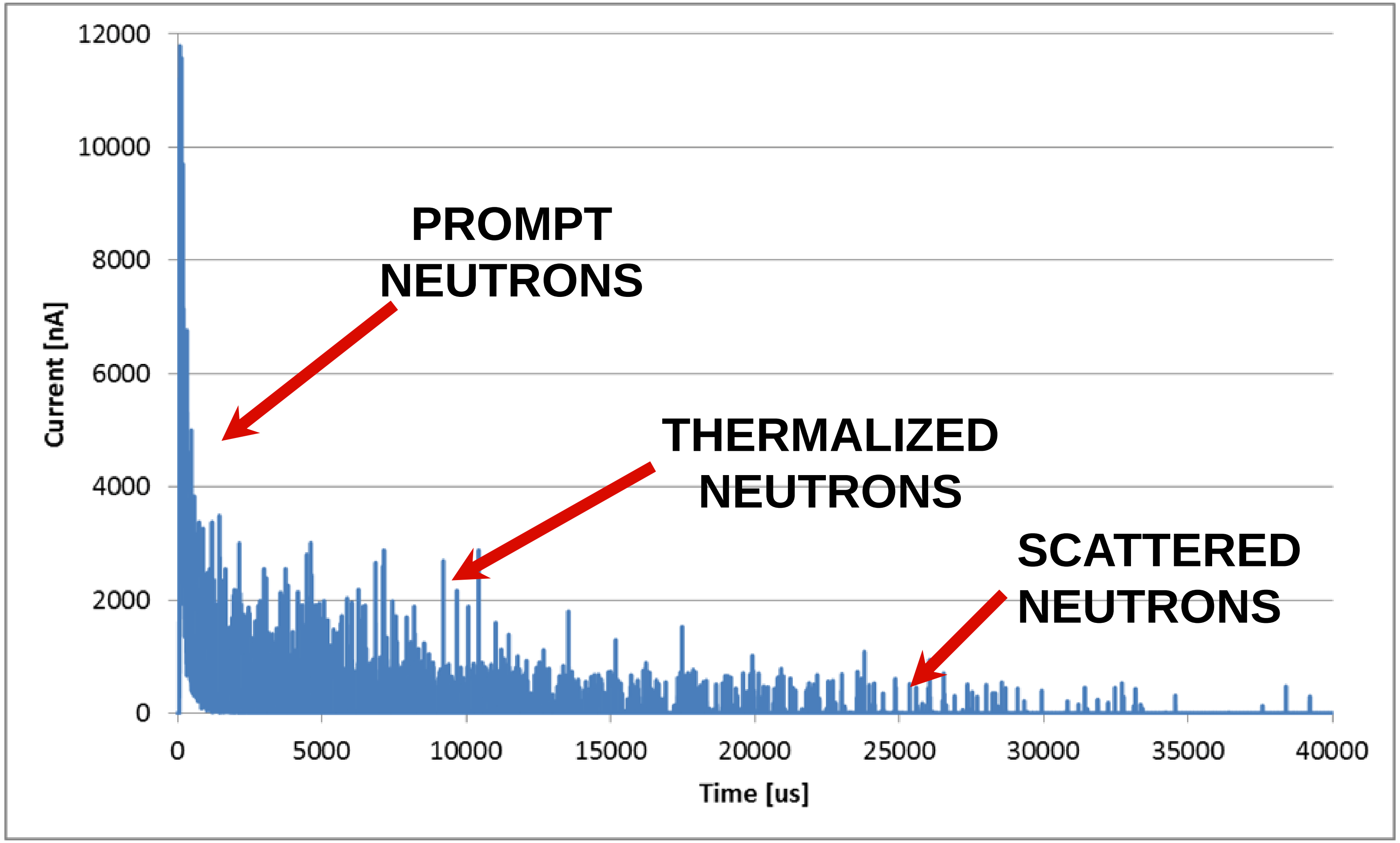
Example of stray field (signal acquired by LUPIN)



E. Aza, M. Caresana, C. Cassell, N. Charitonidis, E. Harrouch, G.P. Manessi, M. Pangallo, D. Perrin, E. Samara and M. Silari. Instrument intercomparison in the pulsed neutron field at the CERN HiRadMat facility. Radiation Measurements 61, 25-32, 2014

Rem counter measurements in a strongly pulsed neutron field

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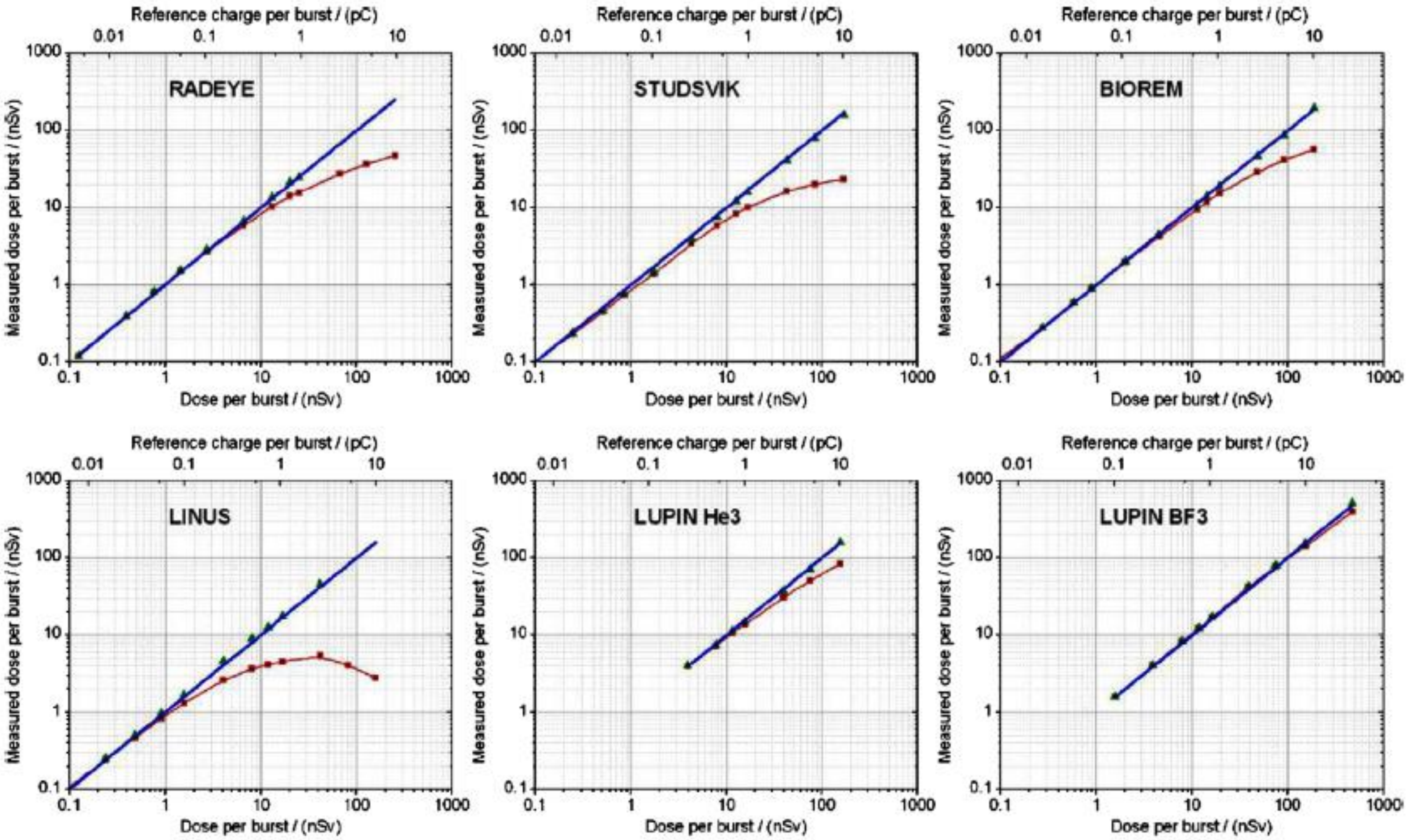

M. Caresana et al. Intercomparison of radiation protection instrumentation in a pulsed neutron field. Nuclear Instruments and Methods A 737, 203–213, 2014.

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For low level contamination / low risk

« Tyvek » overall
(synthetic paper)

Rubber gloves

… generally completed by overshoes

Personal protection equipment against contamination

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For higher levels of contamination = higher risk

- Tyvek overall
- Tape-sealed gloves
- Overshoes
- Respiratory Protective Equipment

Personal protection equipment against contamination

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Whole body protection from contamination




Ventilated, filter and over-pressurized Tyvek

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- With the exception of targets, dumps, collimators, the specific activity (i.e., the activity per unit mass) is not high. However, it is "dispersed" , i.e. the total volume of activated material may be large ⇒ the control of this low specific material represents a major administrative problem (space, cost, elimination pathway)
- Target materials most commonly found are metals (iron magnets, copper or aluminium coils), plastics (cable insulation), stainless steel (vacuum components, pipes), iron, concrete, earth (shielding)
- Accelerator produced radionuclides are different from those identified in reactors ⇒ no fission products or alpha emitters, only β^+, β^- and γ-emitters
- Radiological hazard mainly external. Internal exposure may only result from ingestion or inhalation of radioactive material. Minor contamination risks exist only when surfaces are dusty or become corroded

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Typical medium- and long-lived activation products in metallic components:

^{22}Na, ^{26}Al, ^{54}Mn, ^{55}Fe, ^{56}Co, ^{57}Co, ^{58}Co, ^{60}Co, ^{63}Ni, ^{65}Zn

Activation products in concrete:

^{60}Co, ^{152}Eu, ^{154}Eu and ^{134}Cs

(coming from (n,γ) reactions in trace amounts - a few parts per million or less by weight - of stable europium, cobalt and caesium)

Maximum values of specific activity typically range from a fraction of Bq/g to a few Bq/g

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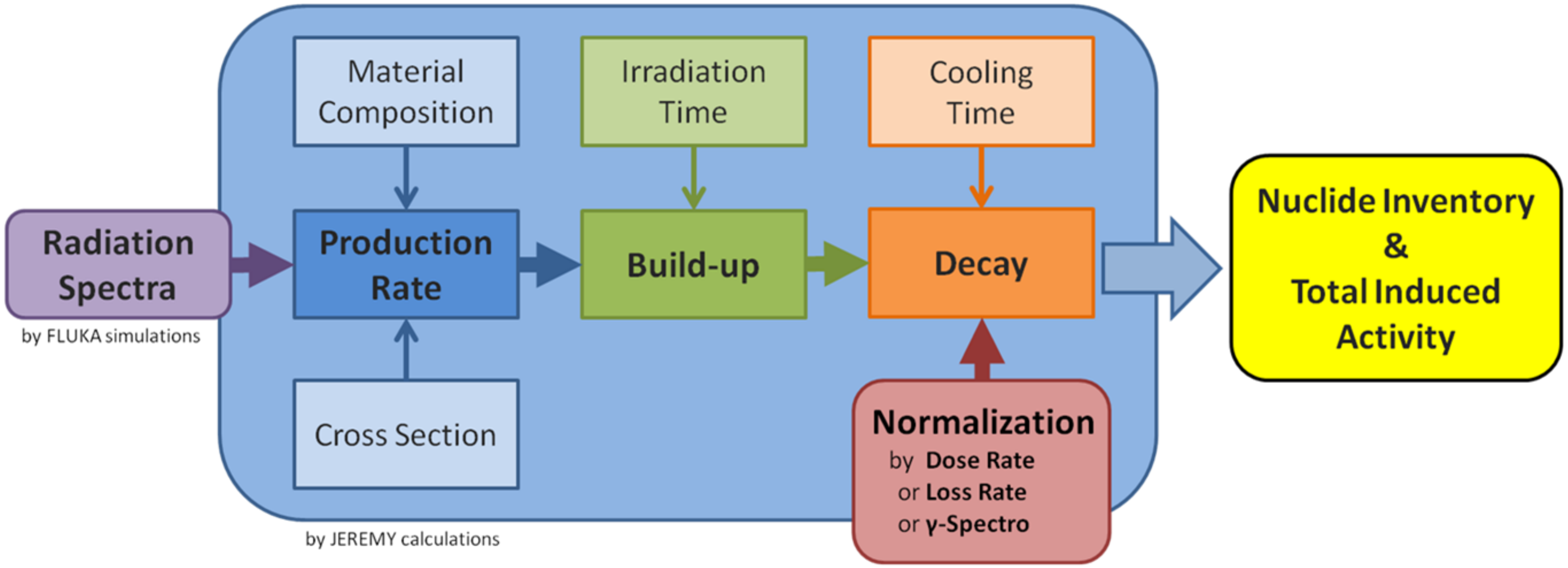
Process to determine the radionuclide inventory



Courtesy Nick Walter, formerly CERN, now CHUV Lausanne

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Preliminary study on the activation of the modules - *Activation sources and irradiation history*

Two activation scenarios:

- 10 to 40 MeV electrons from field emission
- 45 to 100 GeV beam particles

Information:

- During conditioning and operation of LEP only a **few well-localized "hot spots"** of induced radioactivity were produced on one or both **extremities** of the modules (the exit cones)
- **Radioactive decay** since end of 2000 (17 years)
- **Traces** of long lived (half-life > few years) radionuclides expected

No information on:

- **How long** each module was in LEP
- **Irradiation history** of each individual module

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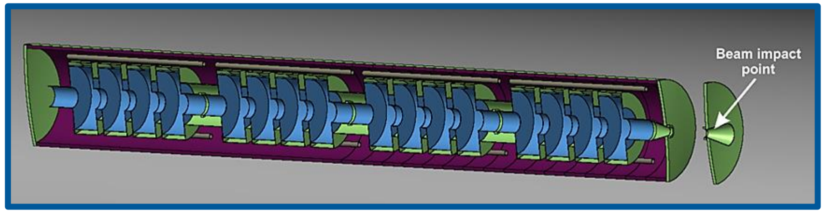
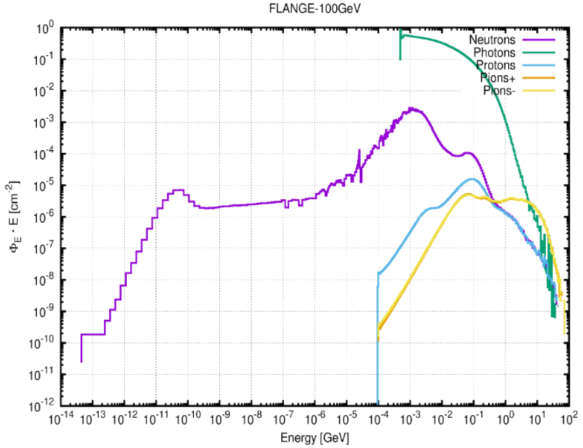
Preliminary study on the activation of the modules - *Monte Carlo Simulations*

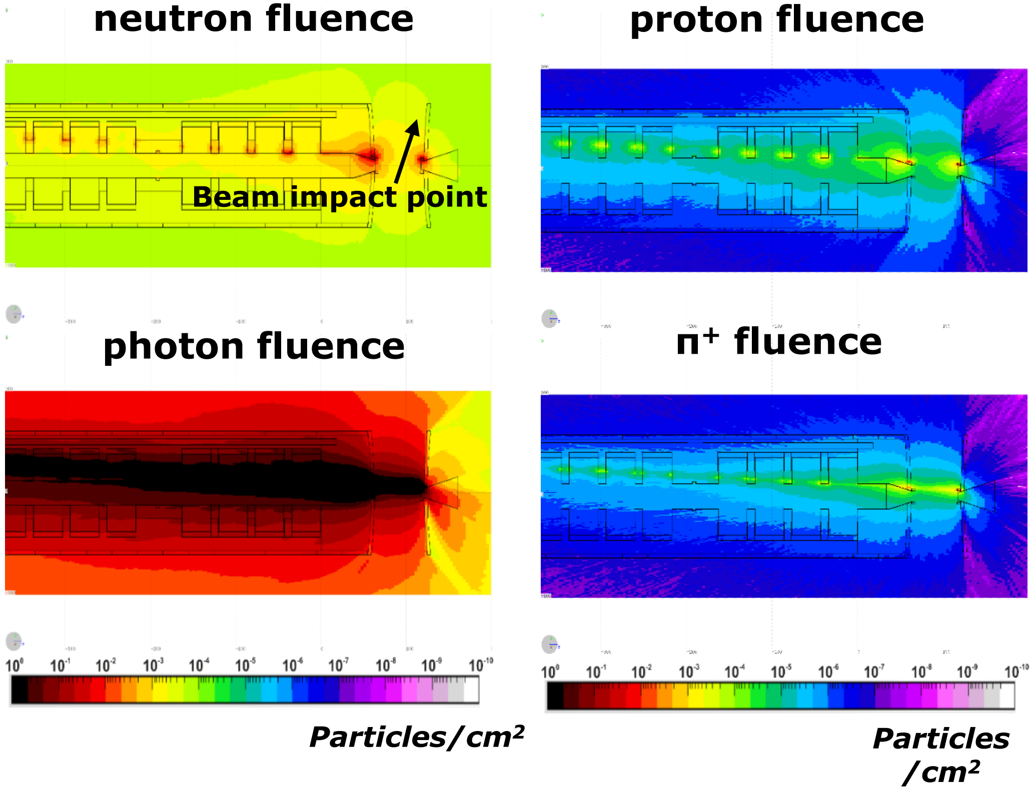
FLUKA simulations of a LEP cryomodule



Particle fluence spectrum – exit cone



Example of 100 GeV electrons impinging on the exit cone (beam losses)



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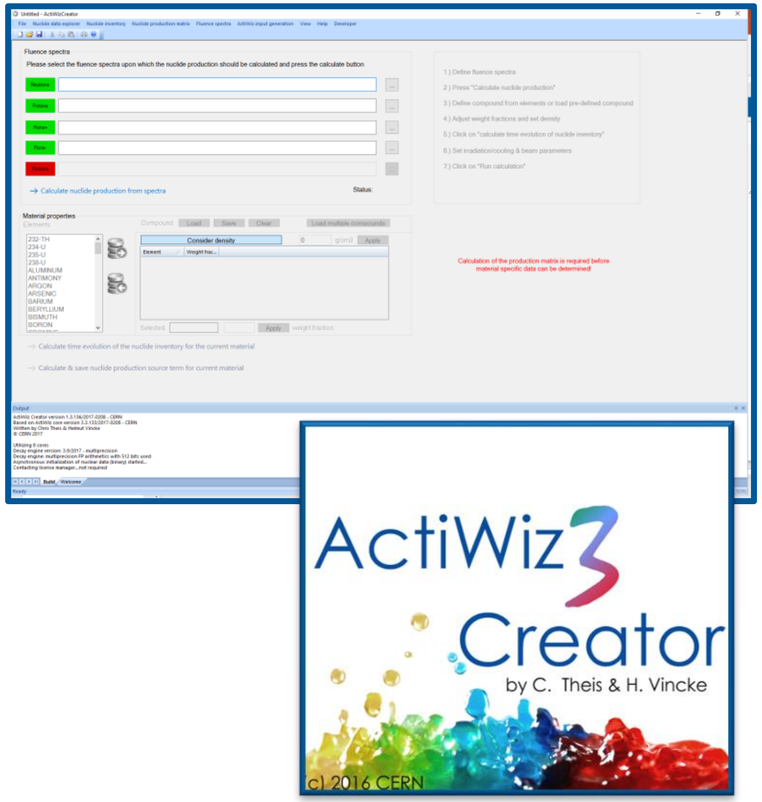
Preliminary study on the activation of the modules

Calculation of nuclide inventories with ActiWiz 3 creator

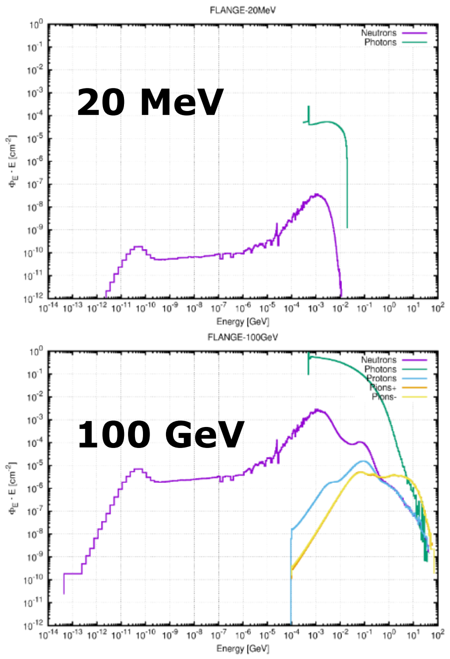
- Software developed and available from CERN
- Analytical code with graphical user interface
  (based on 100 CPU years of FLUKA MC calculations & JEFF 3.1.1 library)
- Evaluation of nuclide inventories within a few seconds to minutes
- Handles arbitrary radiation fields (n, p, pi$^+$, pi$^-$, g) up to 100 TeV
  with fluence spectra as input
- Automatized characterization reports:
  - Dominant isotopes
  - Difficult-to-measure nuclides
  - Impact of chemical impurities
  - …
- A standard tool used for waste & material characterization at CERN



POLITECNICO MILANO 1863
DIPARTIMENTO DI ENERGIA

Preliminary study on the activation of the modules
ActiWiz calculations applied to the LEP cryomodules

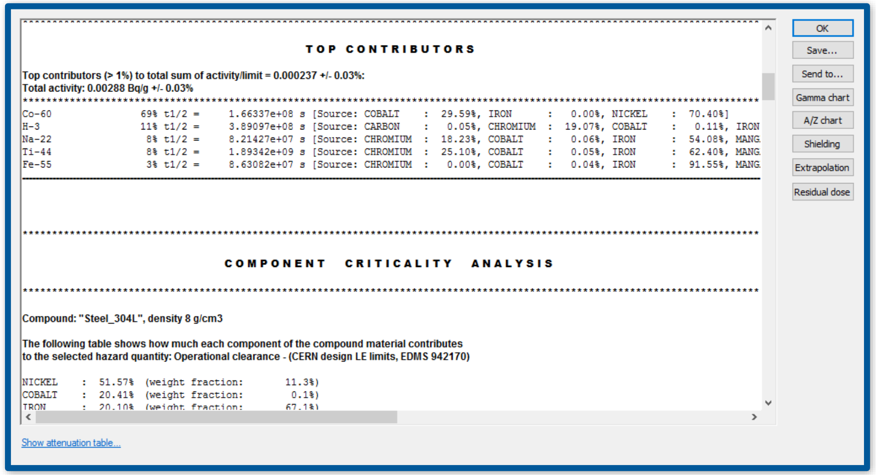
Particle fluence spectra from FLUKA simulations
For each region and material



Irradiation & cooling times

Material composition

ActiWiz calculations



For each region, material and primary energy:

- Nuclide inventory
- Identification of the main contributors (>1%) considering $\sum_i Act_i/LEi$

Na-22, Co-60, Ti-44, Nb-94 (γ-emitters «ETM»)
H-3, Fe-55, Ni-63, Nb-91, Nb-93m (no γ-emitters «DTM»)

- Relative production ratios

CLEAR: Clearance of LEP Acceleration RF system

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Preliminary study on the activation of the modules
Experimental measurements

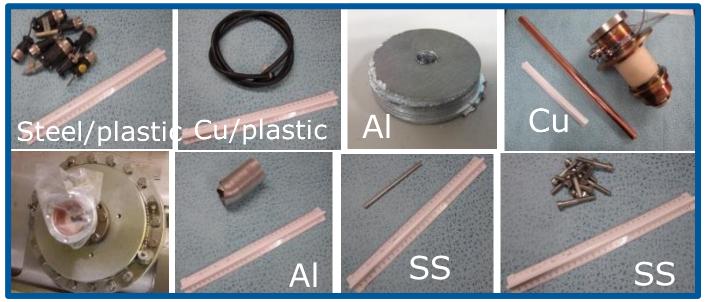
Gamma Spectrometry

CERN RP Analytical Laboratory

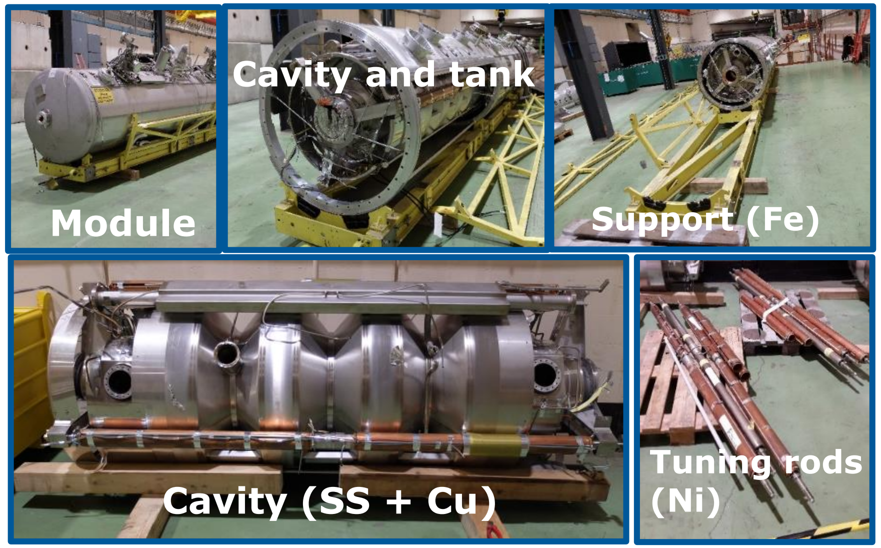
Radiochemical analysis


Amec Foster Wheeler Commercial
amec foster wheeler
Analytical Report for CERN

≈ 100 samples taken from the outer tanks of 8 modules



127 samples taken from the external and internal parts of one module and its cavities



<u>Summary</u>

- γ-spectrometry: only **Co-60** measured with **max. 0.2 Bq/g**
  Na-22 *and* ***Ti-44*** *always below MDA*
- Radiochemical analyses: **H-3, Fe-55, Ni-63** detected

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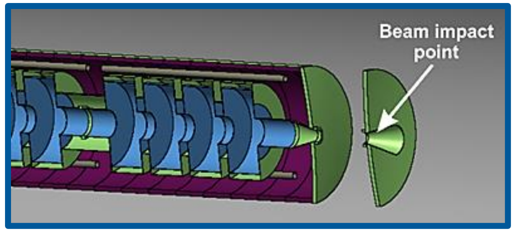
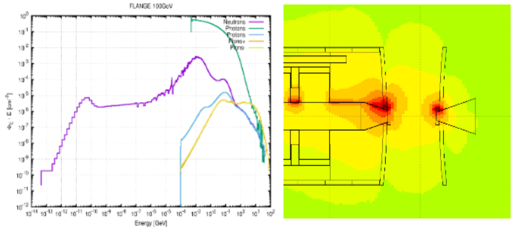
DIPARTIMENTO DI ENERGIA

Preliminary study on the activation of the modules - *Summary*

FLUKA simulations
Monte Carlo





- Particles fluence
- More activated parts

ActiWiz calculations
Software for radiological hazard studies developed at CERN

- Nuclide inventory
- Main contributors
- Activity ratios

Experimental measurements

Gamma Spectrometry

CERN RP Analytical Laboratory

Radiochemical analysis

- Radionuclides activity
- Activity ratios
- Dose rate and contamination

Back to lecture