Radiation safety at CNAO

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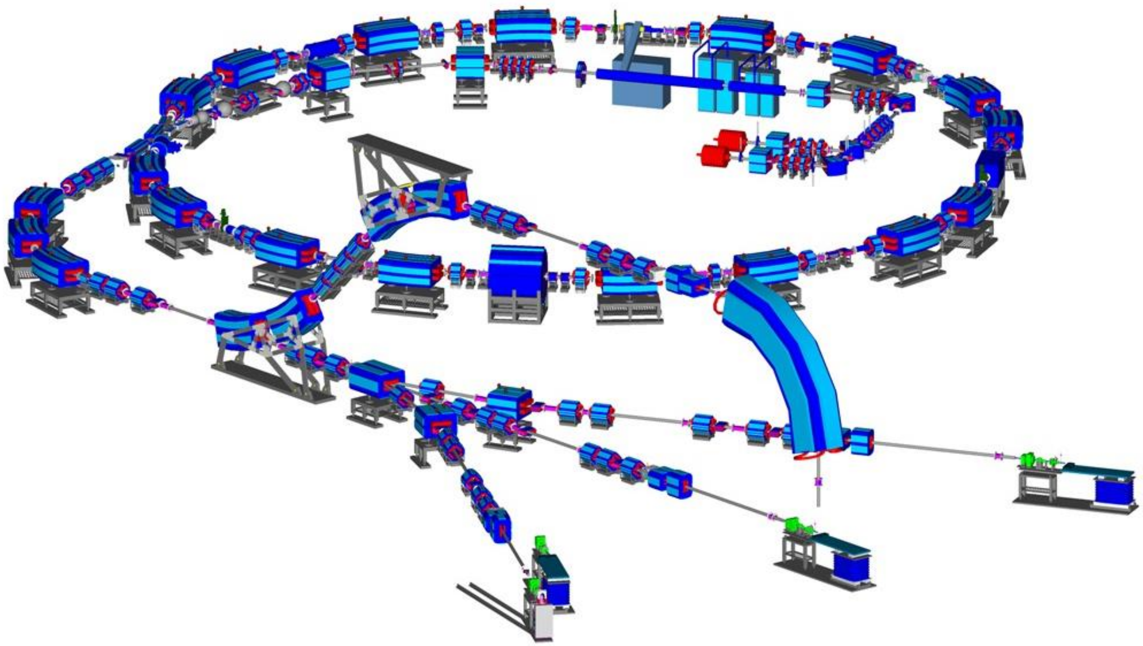
- the radiation safety of facility like CNAO requires a proper solution to many radiation safety problems.

- shielding design

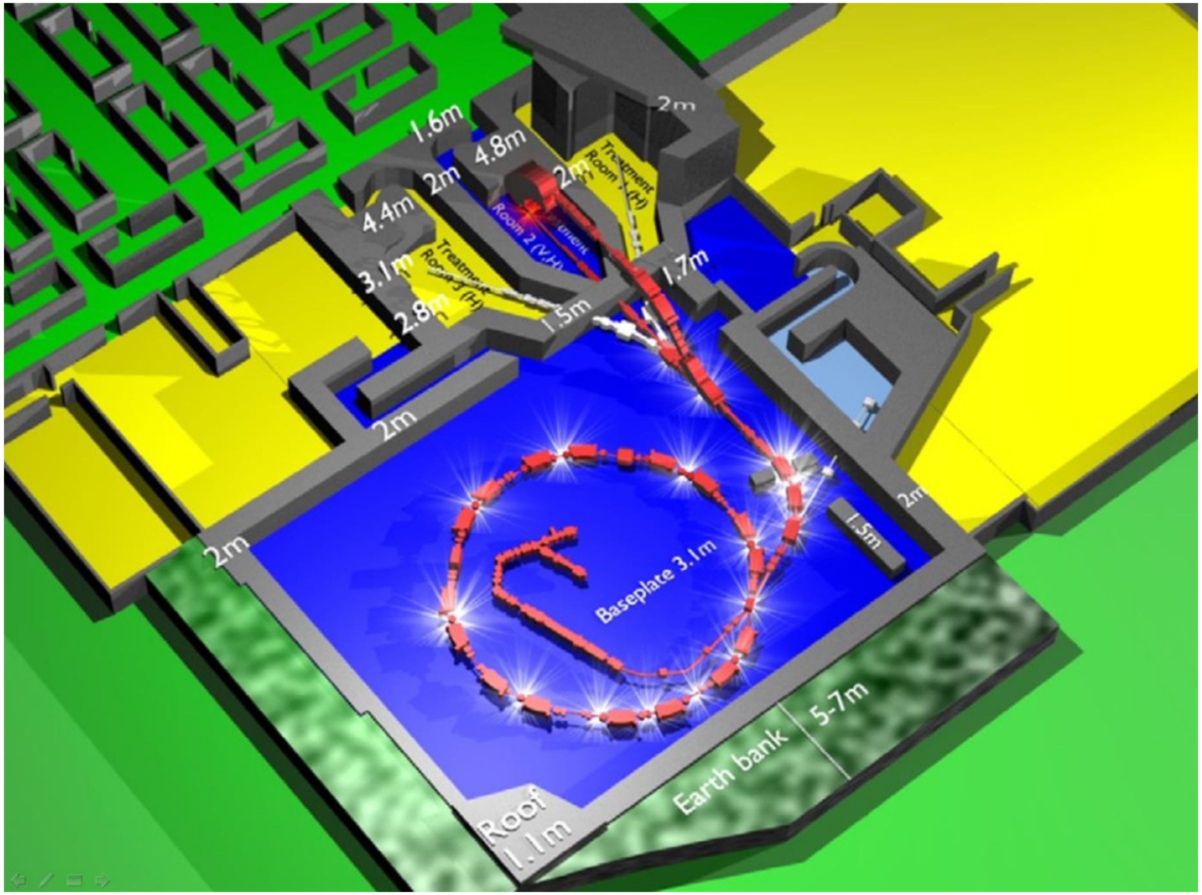
- design of the interlock system

- activations evaluation and measurements



- radiation environmental monitoring for both neutrons and photons (with relevant mixed-field problems)

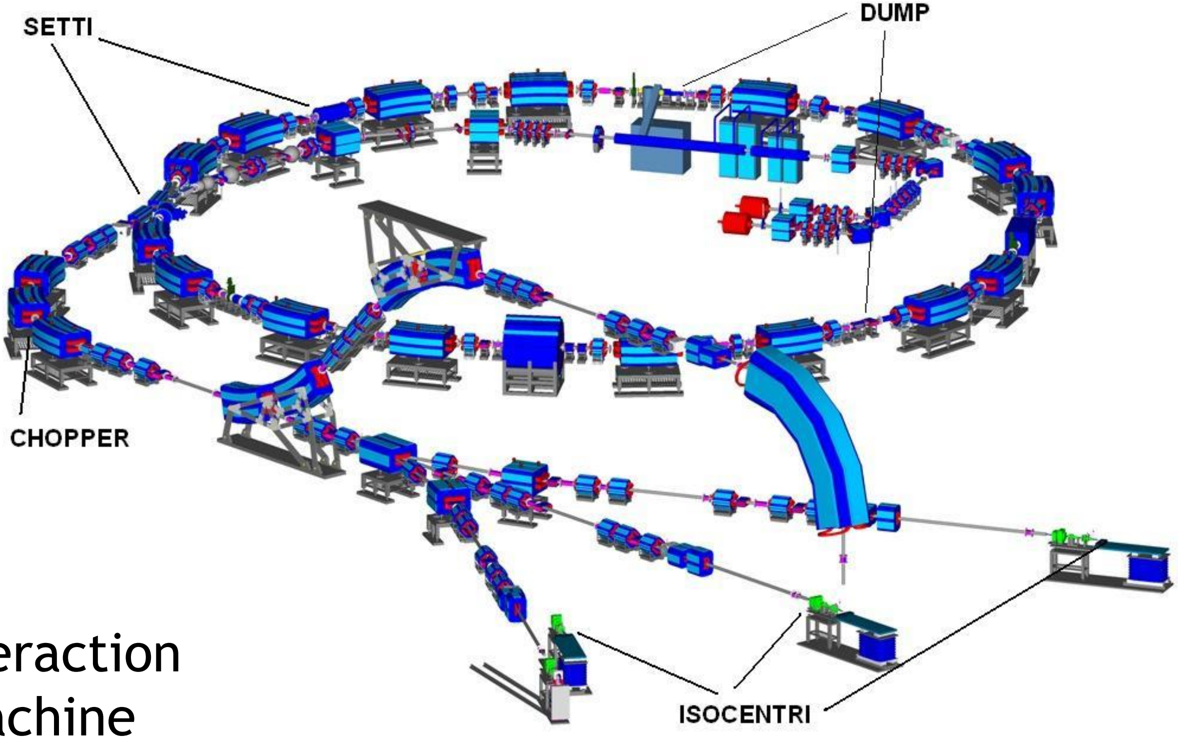
… and many licensing and bureaucratic issues



The shielding of an hadrontherapy centre requires very bulky walls and mazes, which have a noticeable impact on the structural features of the centre. It should be evaluated since the very early stages of the design of the centre.

The shielding design must take into accout:

-the workload, in terms of species, energies and currents of the accelerated particles, and the way the beam is used.

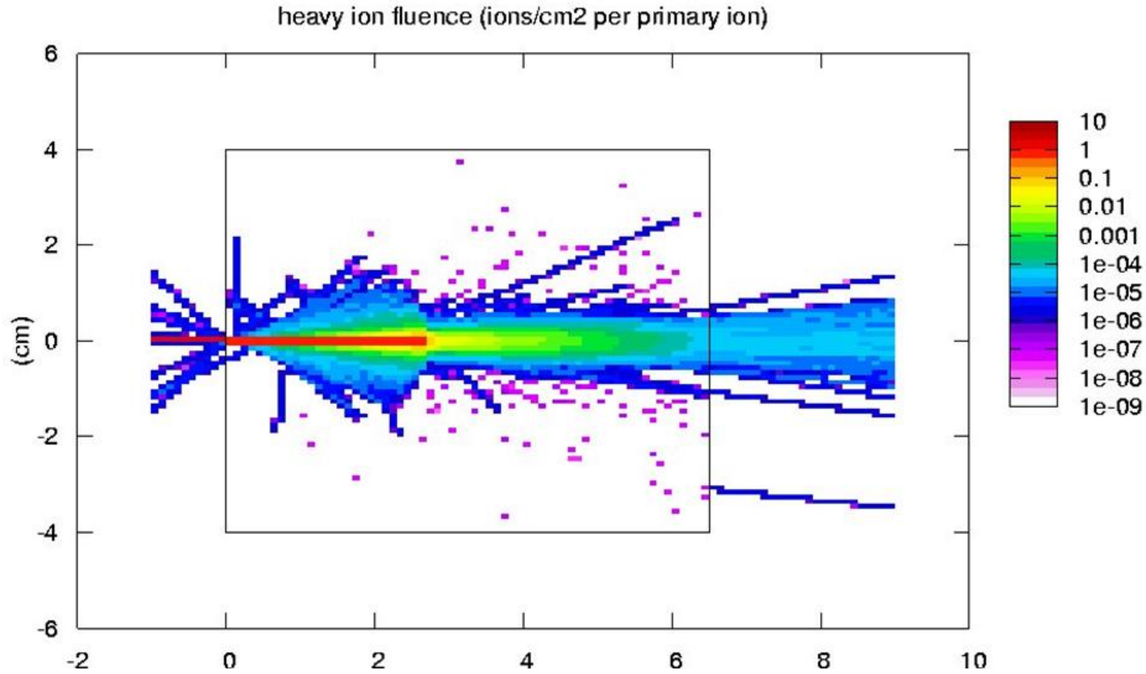


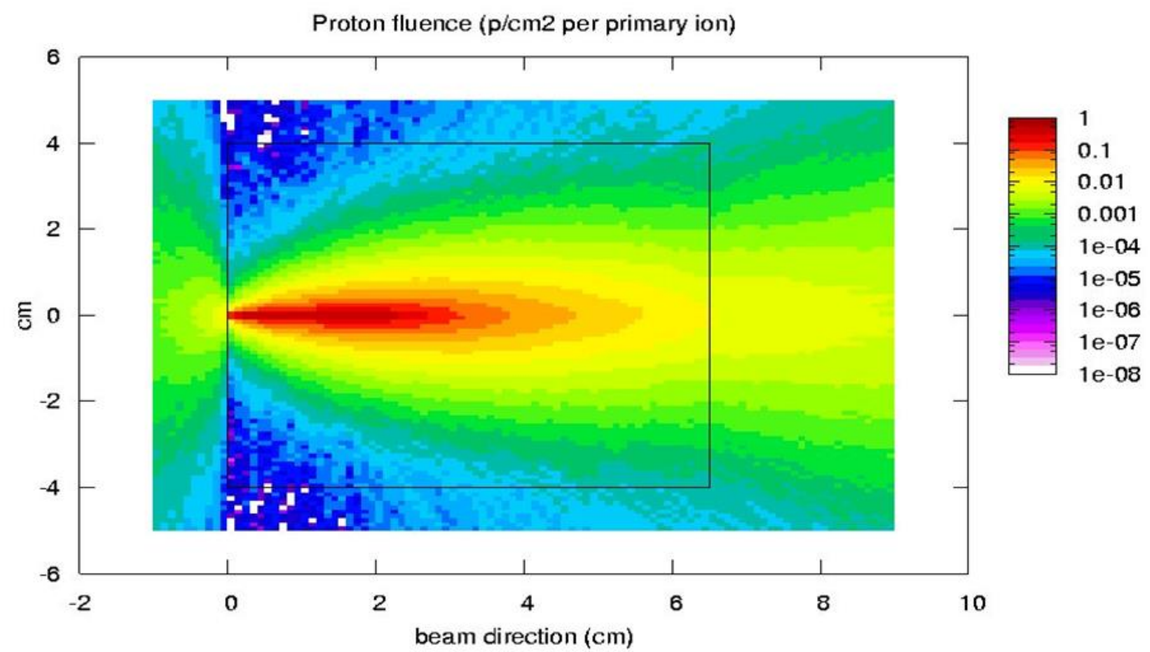
- the points where the interaction between beam and the machine structures (and patients) take place

- the secondary particle generation, and how these secondary particles interact with the shielding

Intermediate energy protons and carbon ions impinging on any material give rise to a complex mixed field, (where many particles can be found, such as neutrons, protons, photons, nuclear fragments etc…)

Heavy charged particles are responsible for the main contribution to the dose inside the treatment or accelerator vault, but they are easily attenuated by the shielding. The radiation field outside the shielding is dominated by neutrons.

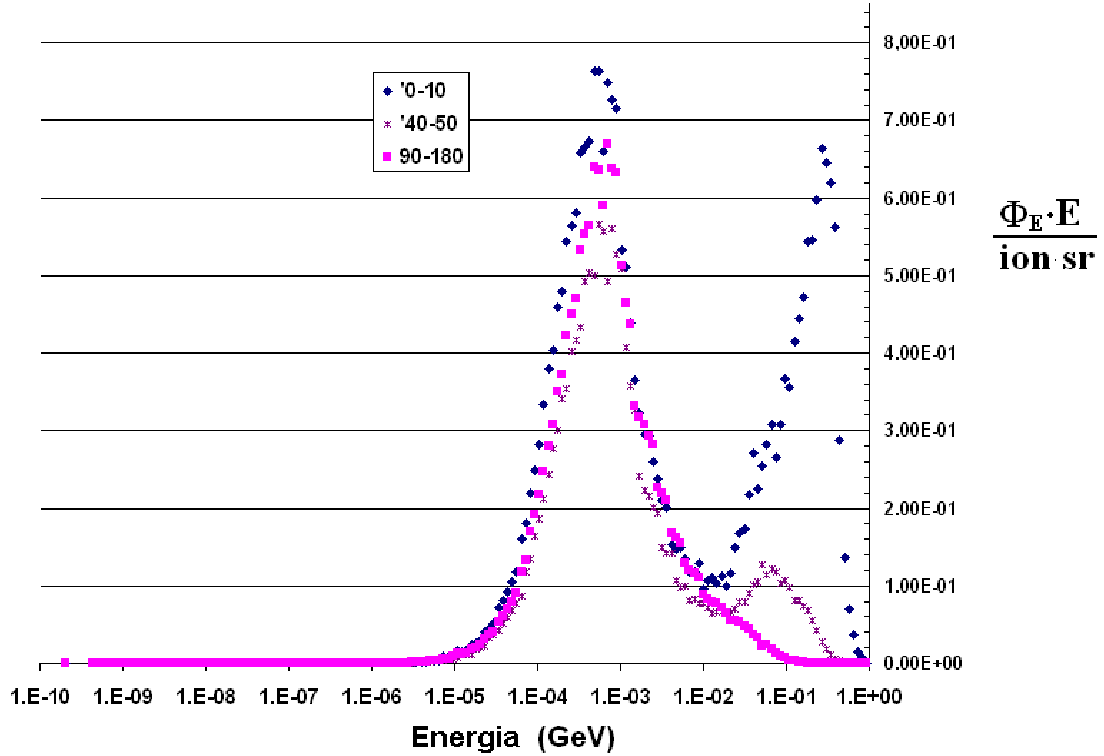




Secondary neutrons are the main contributors to the dose due to stray radiation.

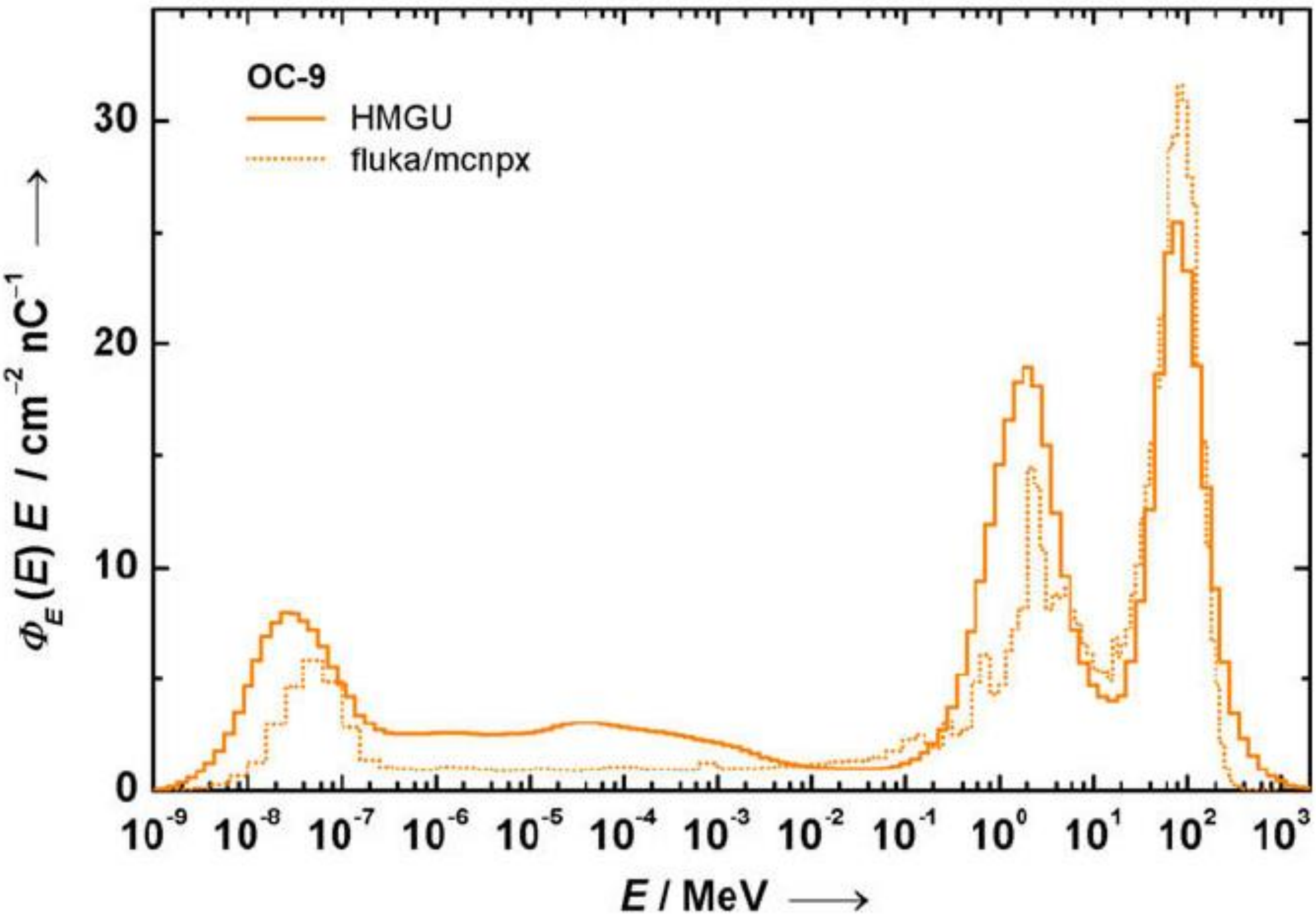
The fluence and energy of secondary neutrons show a very strong dependance on the angle from the beam direction.

The neutron spectra (mainly in the forward direction) have a significant high energy component (up to 1 GeV).



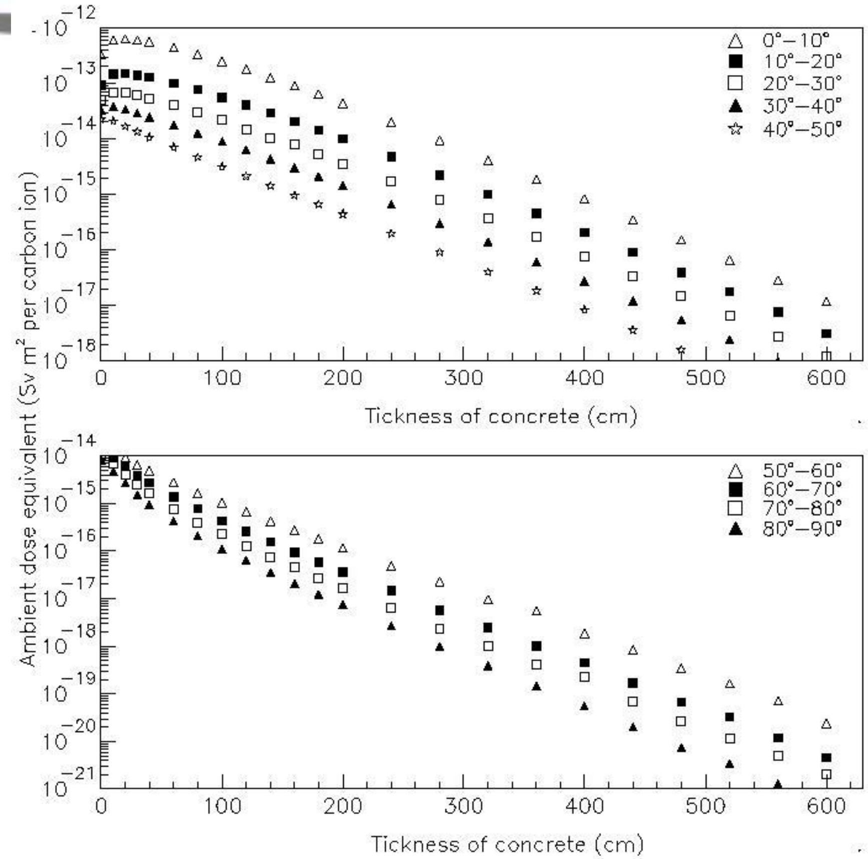
Yield of neutrons produced by a 400 Mev/u Carbon ions beam impinging on a tungsten target

Neutron spectra and yields for many particle kind, energies and for the most commons target materials can be found in literature.



B. Wiegel, et al , *Intercomparison of radiation protection devices in a high-energy stray neutron field, Part II: Bonner sphere spectrometry* Radiation Measurements 44 (2009) 660–672

The attenuation in concrete of neutron fields generated from protons and carbon ions impinging on various targets, at different emission angles, was widely studied in the last 20 years with Monte Carlo simulations (e.g. FLUKA, Geant4, MCNPX etc…).
Moreover, the attenuation can be described by semi-empirical analytical formulas.
For thick shielding (⇔ <50-80-cm) The attenuation can be described as exponential.



Attenuation lenghts (λ) in concrete are somewhere about 100-120 g/cm² ⇔ For 400 MeV/u Carbon ions, the TVL in concrete is somewhere about 1 m.

For protons, source terms and attenuation lenghts are smaller, but currents are usually mich higher

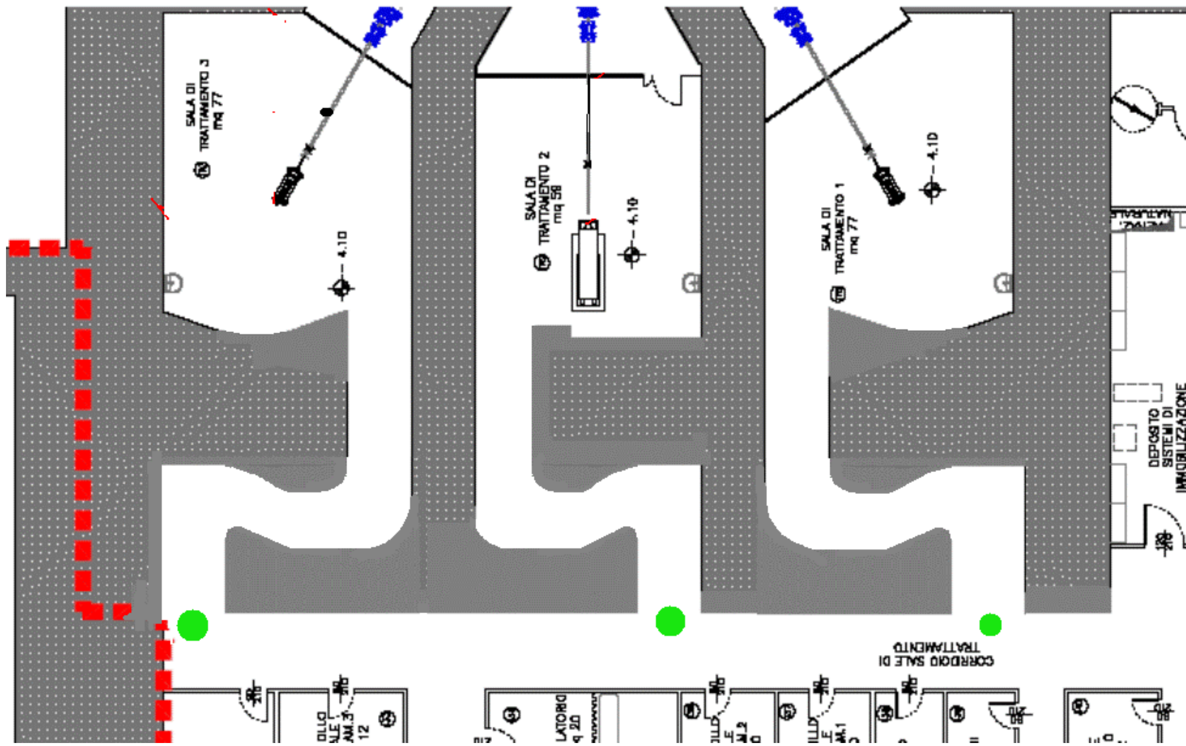
Table 1. Source term and attenuation length in concrete TSF-5.5 for forward and lateral shielding for neutrons produced by 250 MeV protons on thick copper, iron and tissue targets (from Ref. 42).

Angular bin	Fe		Cu		Tissue	
	H_0 per proton (Sv.m²)	λ (g.cm⁻²)	H_0 per proton (Sv.m²)	λ (g.cm⁻²)	H_0 per proton (Sv.m²)	λ (g.cm⁻²)
0°–10°	8.1E–15	108	7.0E–15	110	3.9E–15	95
10°–20°	6.9E–15	107	5.6E–15	108	3.6E–15	93
20°–30°	6.2E–15	101	4.7E–15	106	2.5E–15	92
30°–40°	4.0E–15	98	3.5E–15	100	1.8E–15	83
40°–50°	2.9E–15	96	2.5E–15	97	9.3E–16	80
50°–60°	2.0E–15	92	1.8E–15	91	7.1E–16	75
60°–70°	1.2E–15	85	1.1E–15	82	6.0E–16	67
70°–80°	7.6E–16	74	7.1E–16	72	5.0E–16	59
80°–90°	6.0E–16	64	5.7E–16	63	3.0E–16	52

Reflected radiation (ducts and mazes)

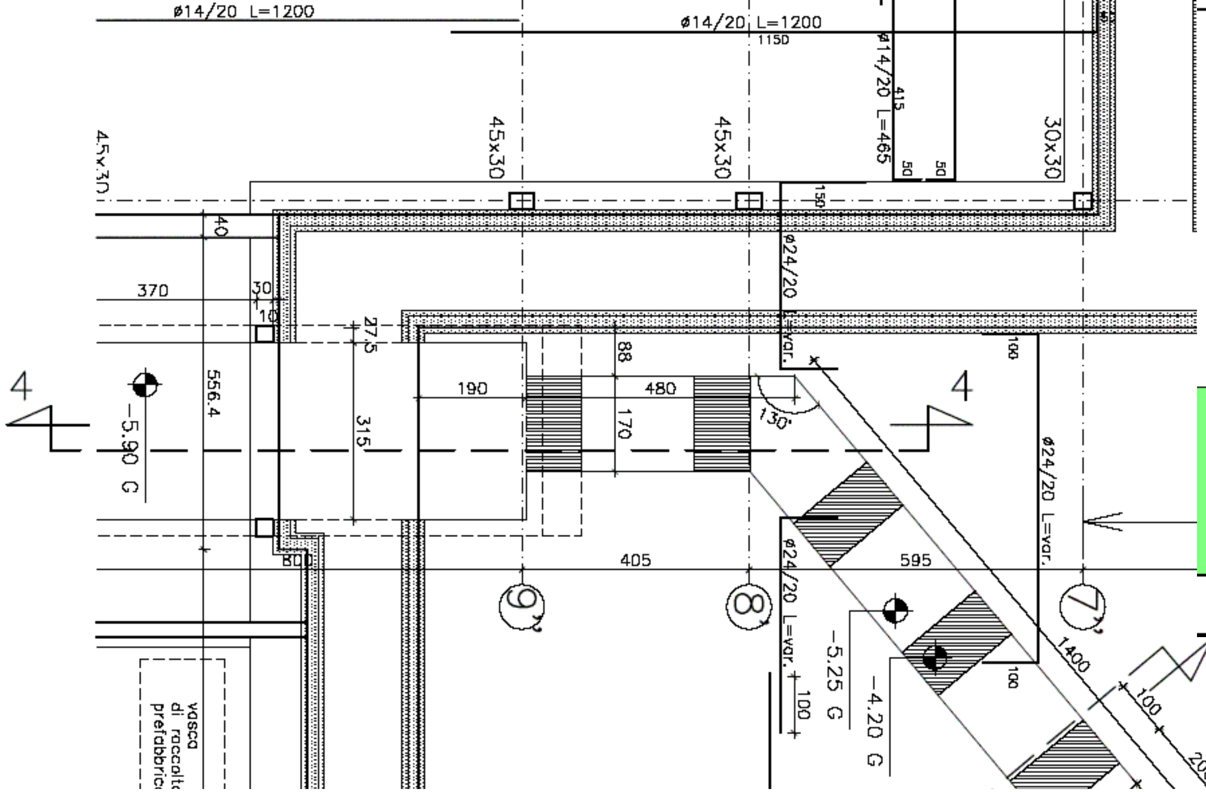
The mazes design must take into account both the transmitted and the reflected radiation.

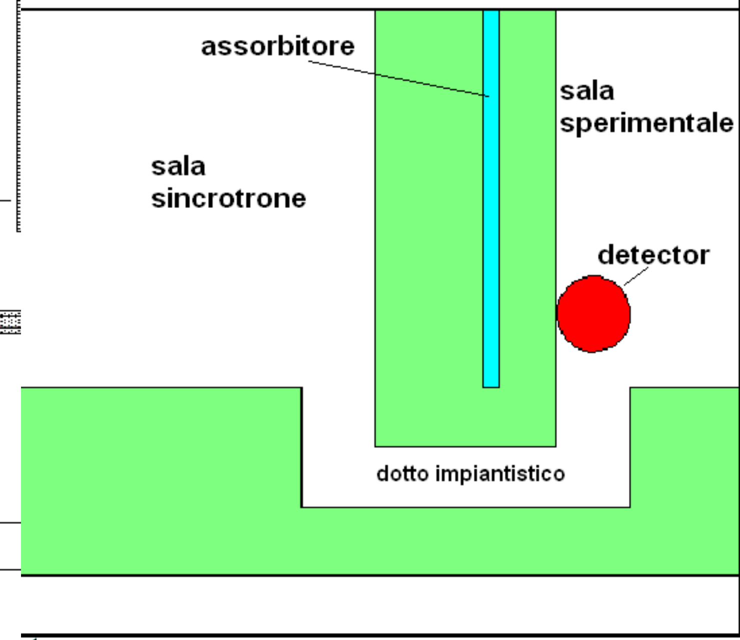
There are no reflection coefficients for high energy neutrons.



The design is based on universal curves and verified with Monte Carlo simulations.

The mazes design obviously depend on which doors are required (e.g. at CNAO we have no shielding doors).






```
 10/04/07 15:45:02
===> buco schermature CNAO 2
 <===

probid =   10/04/07 15:44:39
basis:
( 1.000000, 0.000000, 0.000000)
( 0.000000, 0.000000, 1.000000)
origin:
(     0.00,   100.00,     0.00)
extent = (  1000.00,  1000.00)
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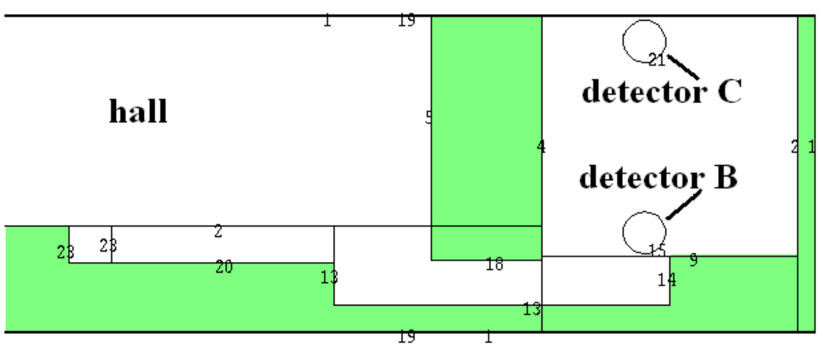


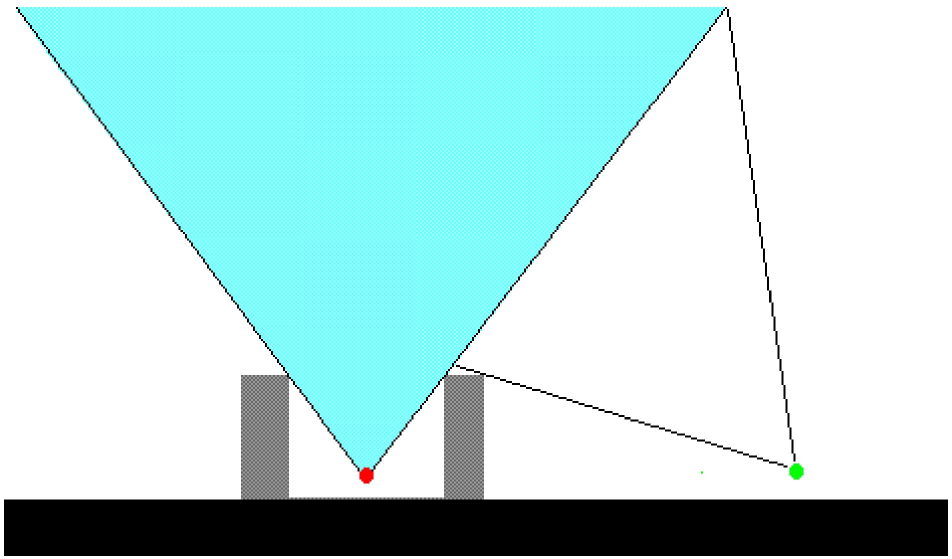
The same problem is to be solved for piping ducts.

In literature many semi-empirical universal curves are given. The are usually not so precise enough to fully handle the problem (simulations are always required).

Skyshine

Hadrontherapy centres usually have very large roofs.
The roof shielding is to be dimensioned on neutron skyshine, taking into account what is in the nighbourhood.
Since hadrontherapy centres are usually built in in crowded areas, this is often a serious issue.

The roof shielding is usually not calculated (only) in order to reduce the dose to peopole walking on it. The main goal is to reduce the dose contribution due to neutrons reflected by the atmosphere all around the plant (skyshine).



The skyshine depends on the number of neutrons emitted by the roof ⇔(dose on the roof * roof area).

Skyshine is a critical issue in crowded areas
(and CNAO is in the middle of a city).

The skyshine evaluation requires Monte Carlo simulations (and a cross check with many semi-empirical formulas that can be found in literature)


DINI


DINI
AUTOGRU
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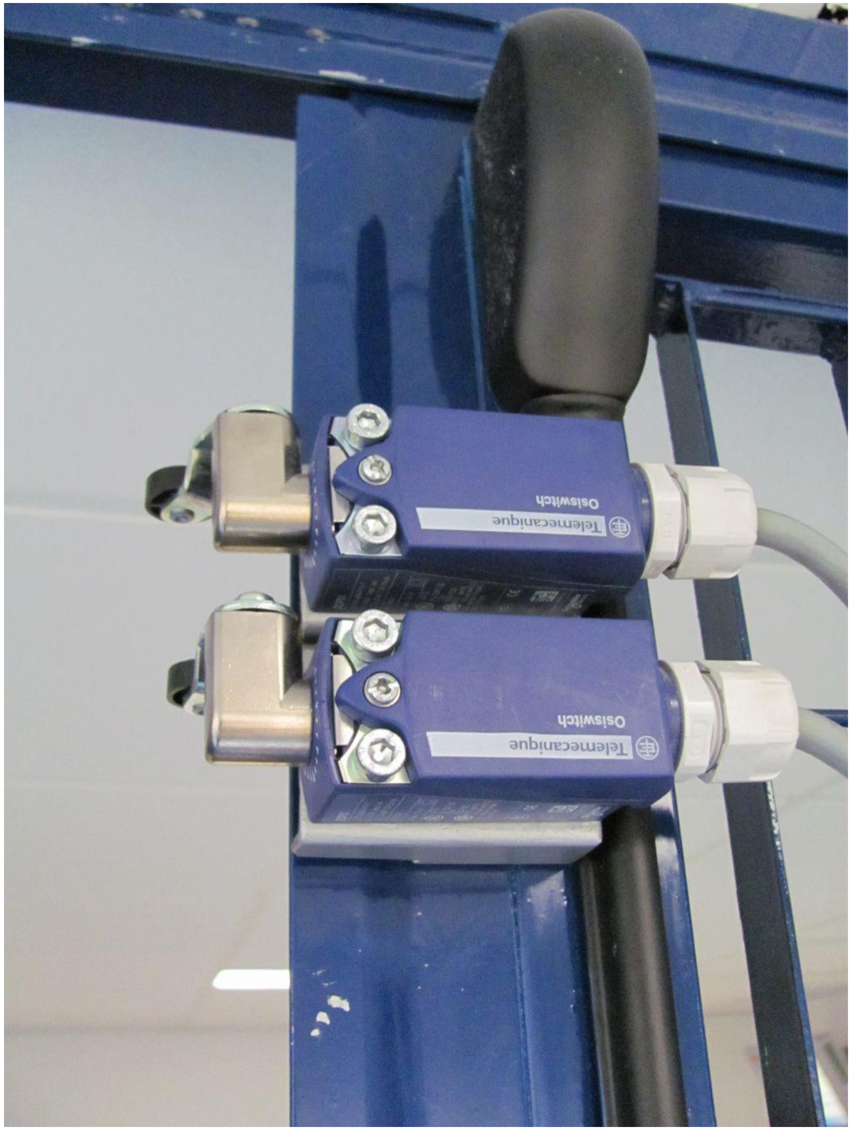
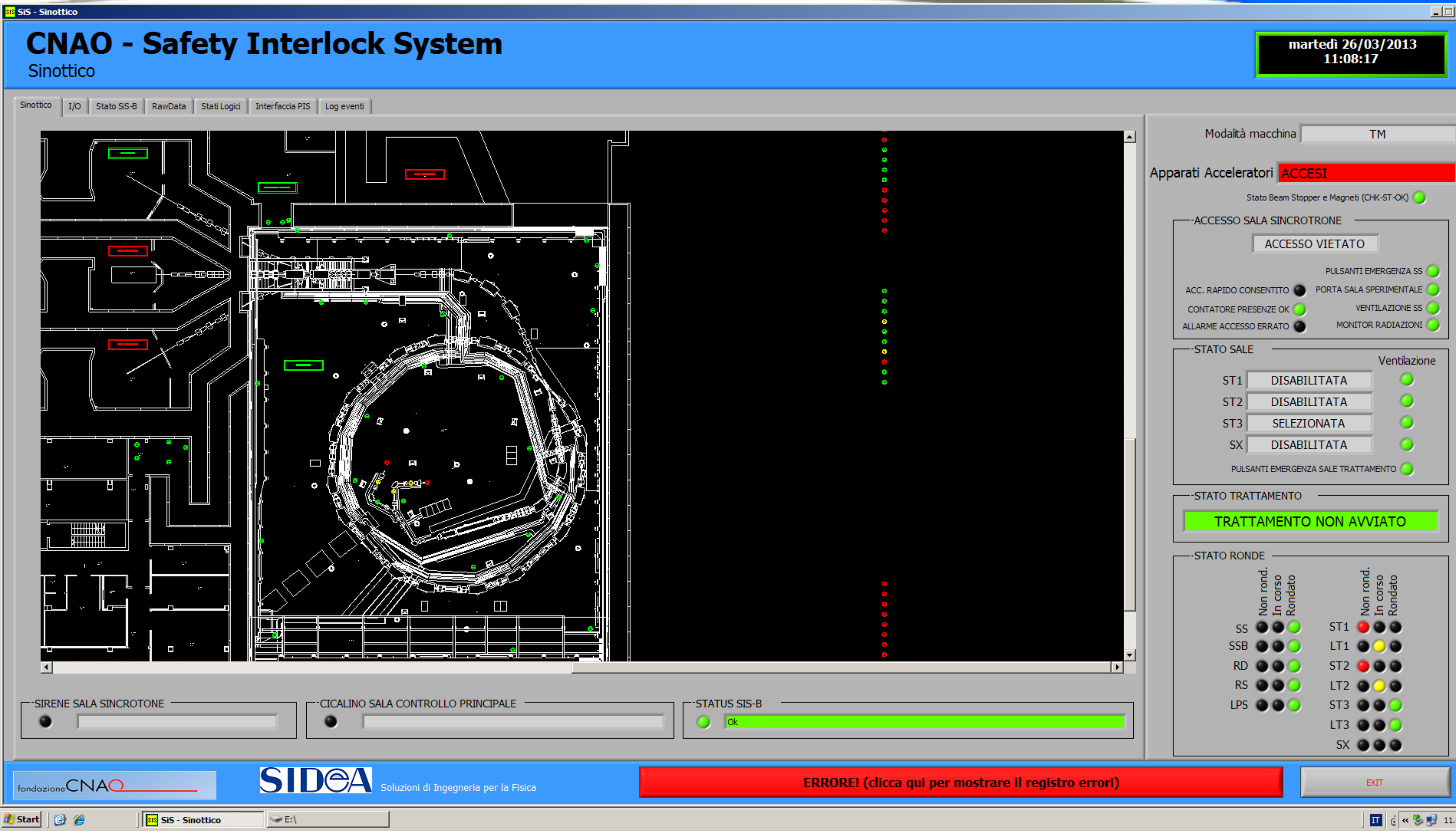
AUTOGRU
LIEBHERR
DINI
PARMA
S-85
S-85

SIS (Safety Interlock System)

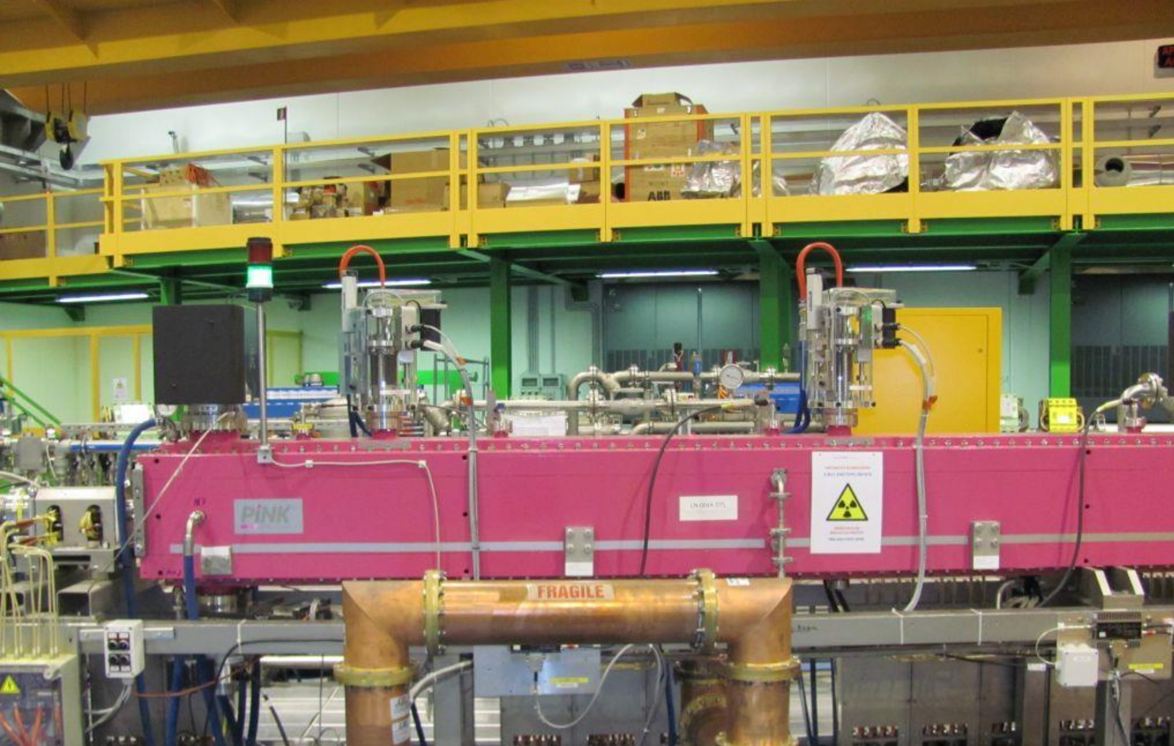
At CNAO the safety interlock system has been evaluated with particular care with respect not only to the personnel safety (that is a given) but also for the patient safety during the treatment.

It takes into consideration more than 450 signals, and it
- gives veto to any radiation emitting device
- handles information from the machine, from the doors and turnstile of the synchrotron hall, from the radiation monitors and from emergency buttons all over the plant.





In order to protect the patient too and to minimize the impact on the clinical activities, the SIS adapts its behaviour accordingly to the status of the machine.
It also handles the signalling (sirens, lights etc..)


PINK
FRAGILE


CNAO - Safety Interlock System
Stato Macchina
Tuesday 23/11/2010
11:04:30
MODALITA' QUALITA'
STATO DI FUNZIONAMENTO MACCHINA SPENTA
STATO SALA 1 ABILITATA
ACCESSO CONTROLLATO
PRESCRIZIONI DOSIMETRO PERSONALE
SIDeA
Soluzioni di Ingegneria per la Fisica
fondazione CNAO


APPARATI
ACCESI

Activations

The beam activates any material it impinges on.

Activations are a serious issue: they are usually the primary contributor to the dose received by the personnel working in accelerator environment.

They must be taken into account to regulate:

- the access modalities to the synchrotron area and to the treatment rooms

-for the maintenance on machine parts, on cooling water and air filters

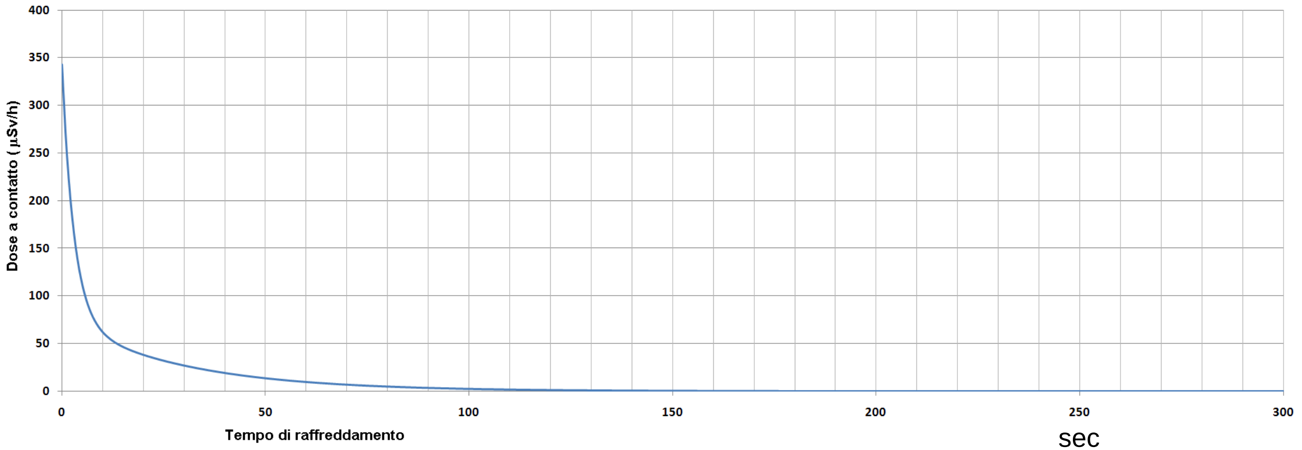
Also air and cooling water get activated

Activations are to be taken into account for the disposal of machine parts, but also for any irradiated material (not only filters and bolts, but also the patients’ positioning masks, sheets etc…).

At the moment, activations on the machine lines provide a negligible dose to the operators.

Activations in the treatment rooms (QA water phantoms, patients etc…)

when irradiating light materials, (water, TE phantoms),O-15 (T½ 2.02 min), N-13 (T½ 9.97 min) and C-11 (T½ 20.38 min) are formed

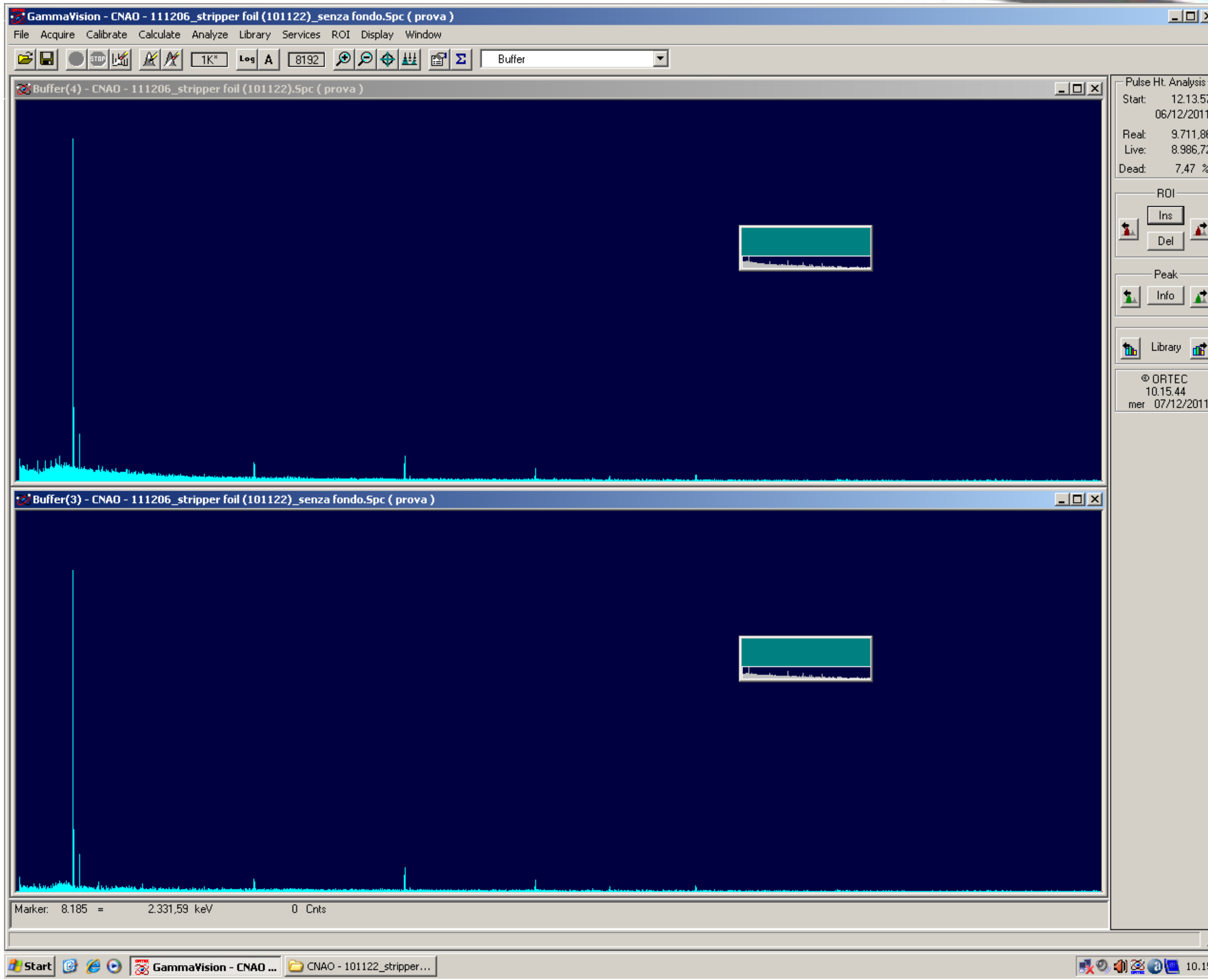


During the machine setting, “high” dose rates (up to 400 µsv/h) happen to be measured in on the beam dumps, but the radiaoctive decay is quite fast (in a few minutes the dose rates get much lower).

During the clinical activities, lower currents are used, and the dose rates in the treatment rooms are usually lower.

Anything that has been irradiated is carefully checked before being allowed out of the plant.

Es. the samples are measured with HpGe spectrometers, in order to fully characterize the material activation.

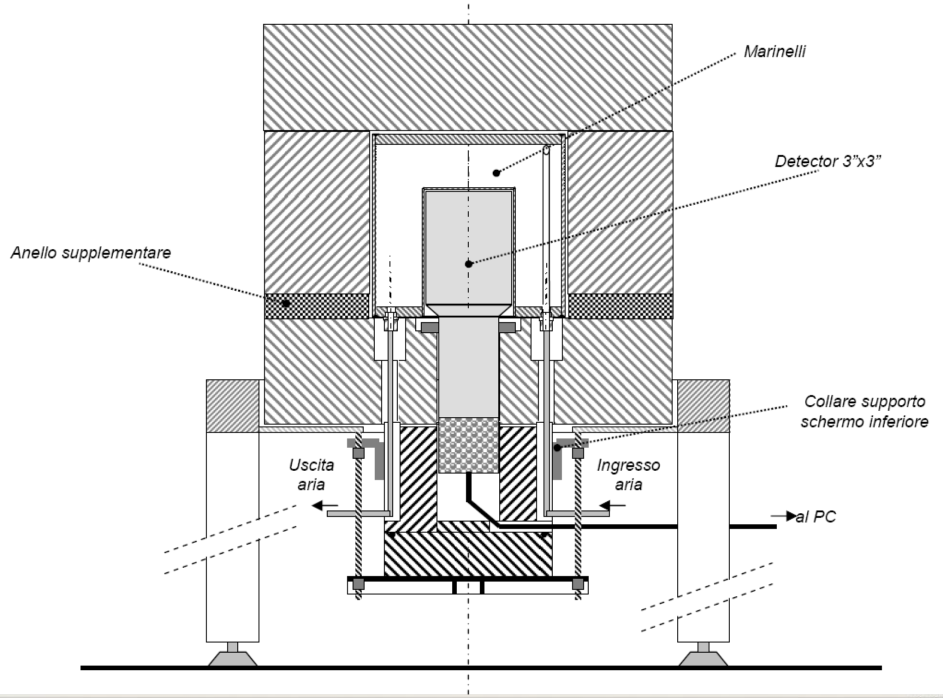


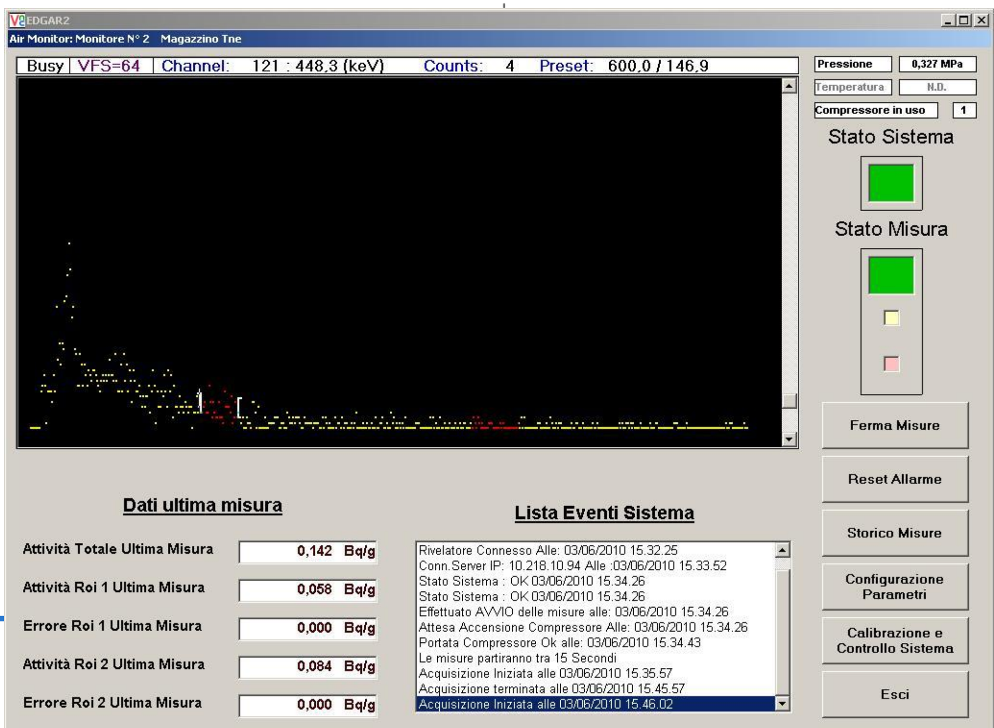
Activation in air

In air the same nuclides (β+ emitters) are formed.
The concentration are very low (< 1 Bq/g) and measuring it is a difficult task.

The air in the air draining pipe is continuously sampled, compressed and measured in a Marinelli beaker with a NaI detector.

In this way a LLD of about 20 mBq/g is obtained (but it depends on the sampling time).



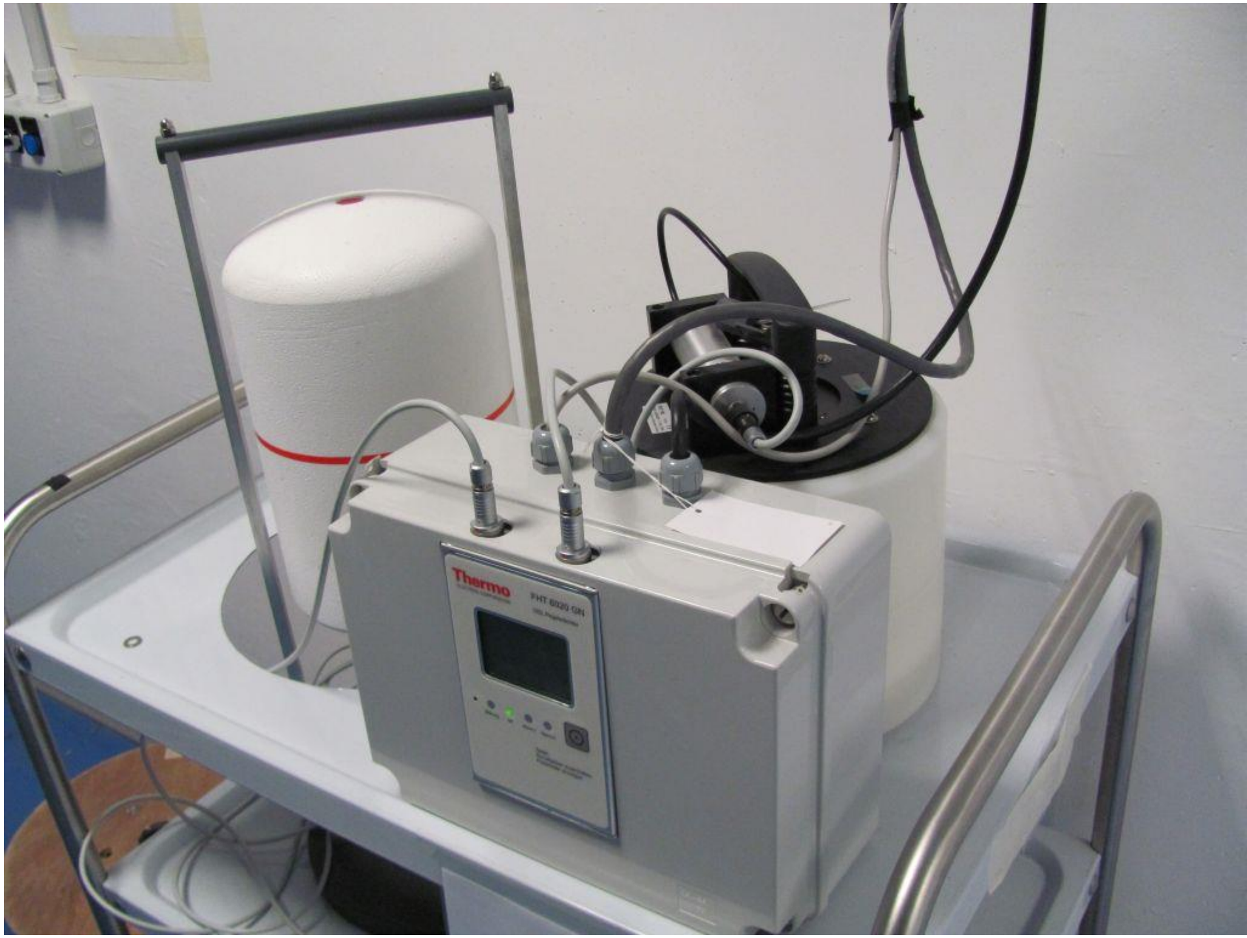


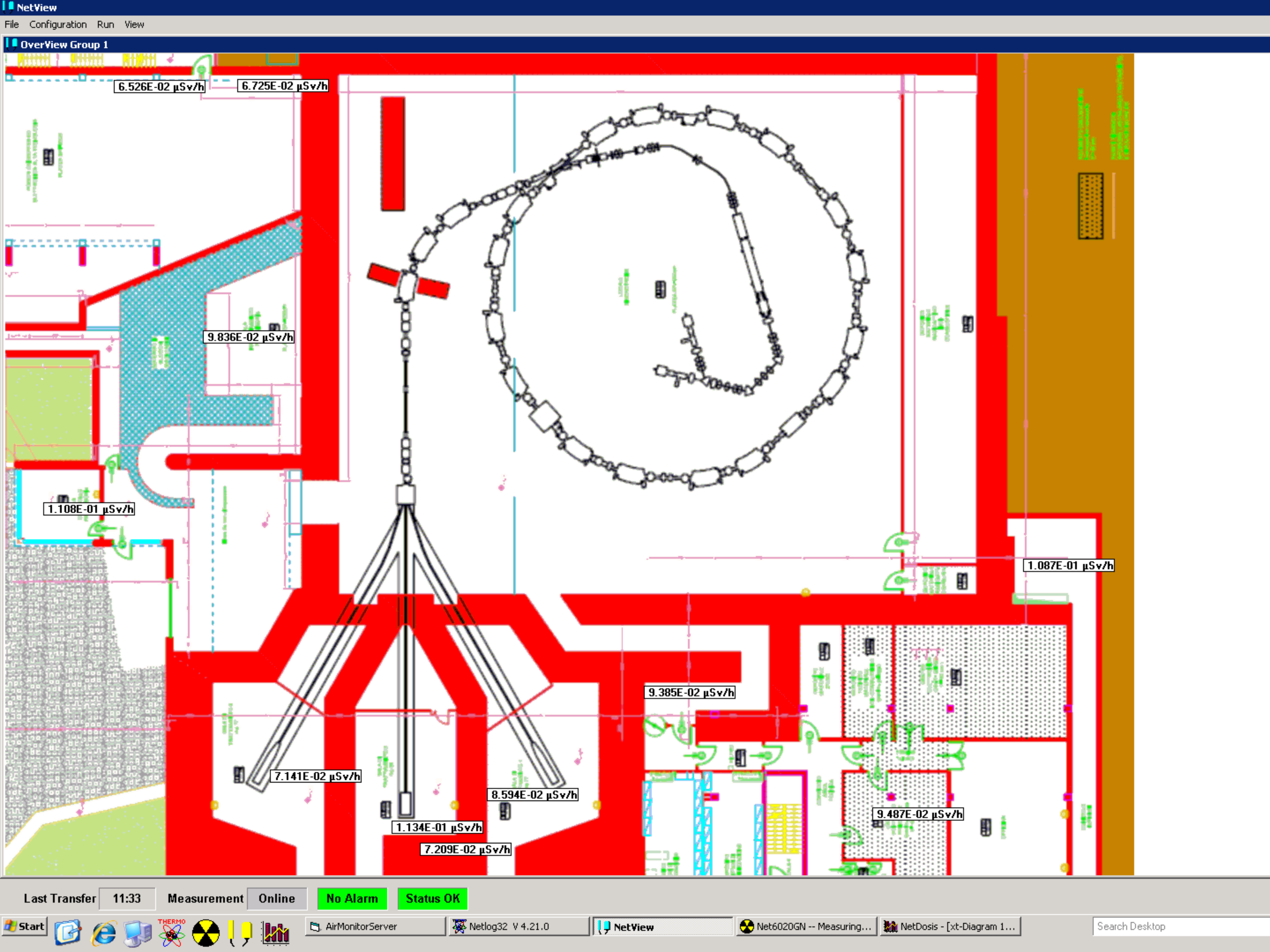
Environmental monitoring

11 active n,γ stations are deployed around the machine: 3 inside the treatment rooms, and 8 out of the shielding.

They are based on two monitors: a pressurized ionization chamber and an extended range Rem counter (Thermo electron Wendi).

They give an interlock if the dose rate rises above a certain threshold and they log the dose rate continuously.




NetView
File Configuration Run View
OverView Group 1
6.526E-02 µSv/h
6.725E-02 µSv/h
9.836E-02 µSv/h
1.108E-01 µSv/h
1.087E-01 µSv/h
9.385E-02 µSv/h
7.141E-02 µSv/h
8.594E-02 µSv/h
1.134E-01 µSv/h
7.209E-02 µSv/h
9.487E-02 µSv/h
Last Transfer 11:33
Measurement Online
No Alarm
Status OK
Start
AirMonitorServer
Netlog32 V 4.21.0
NetView
Net6020GN -- Measuring...
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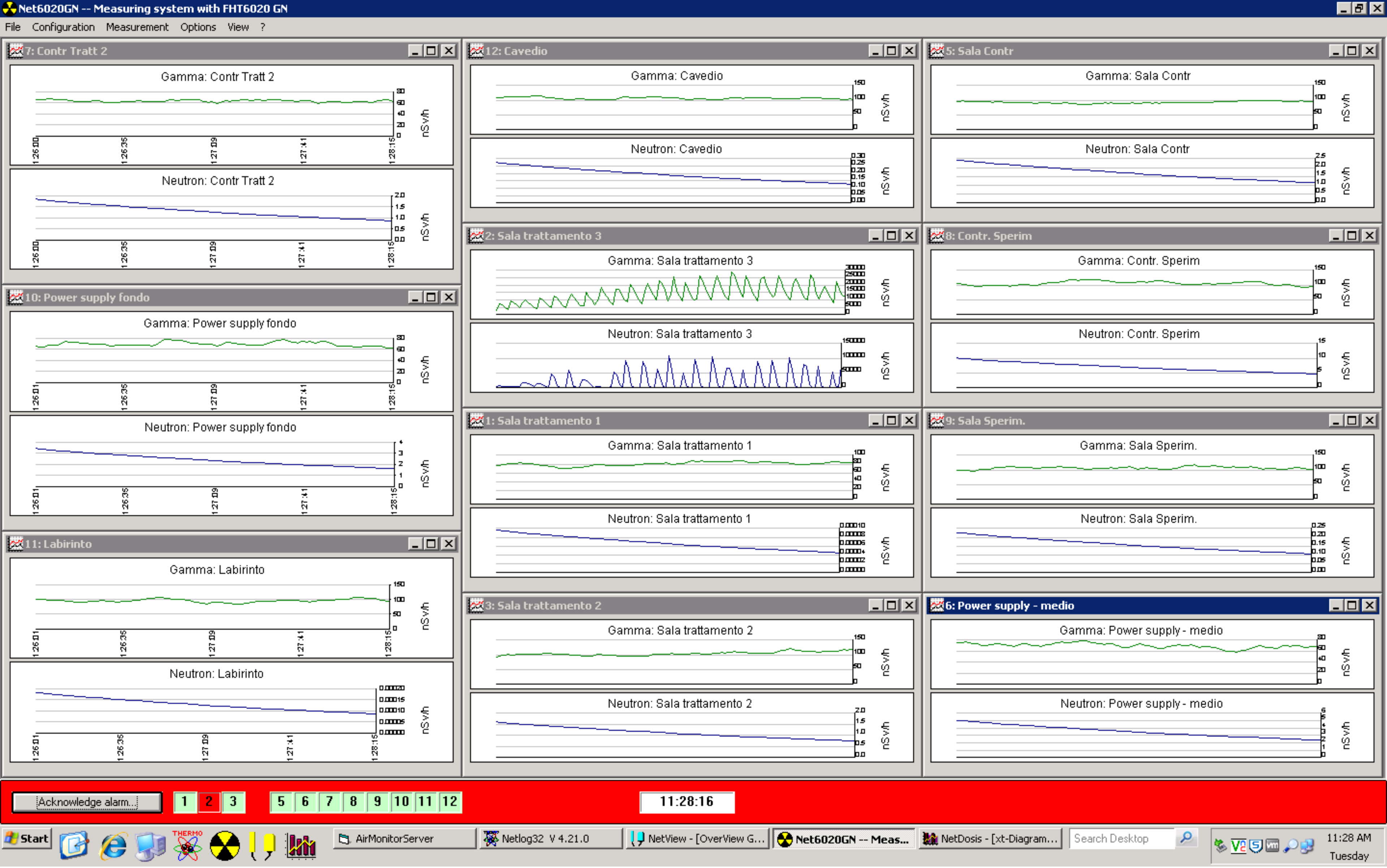
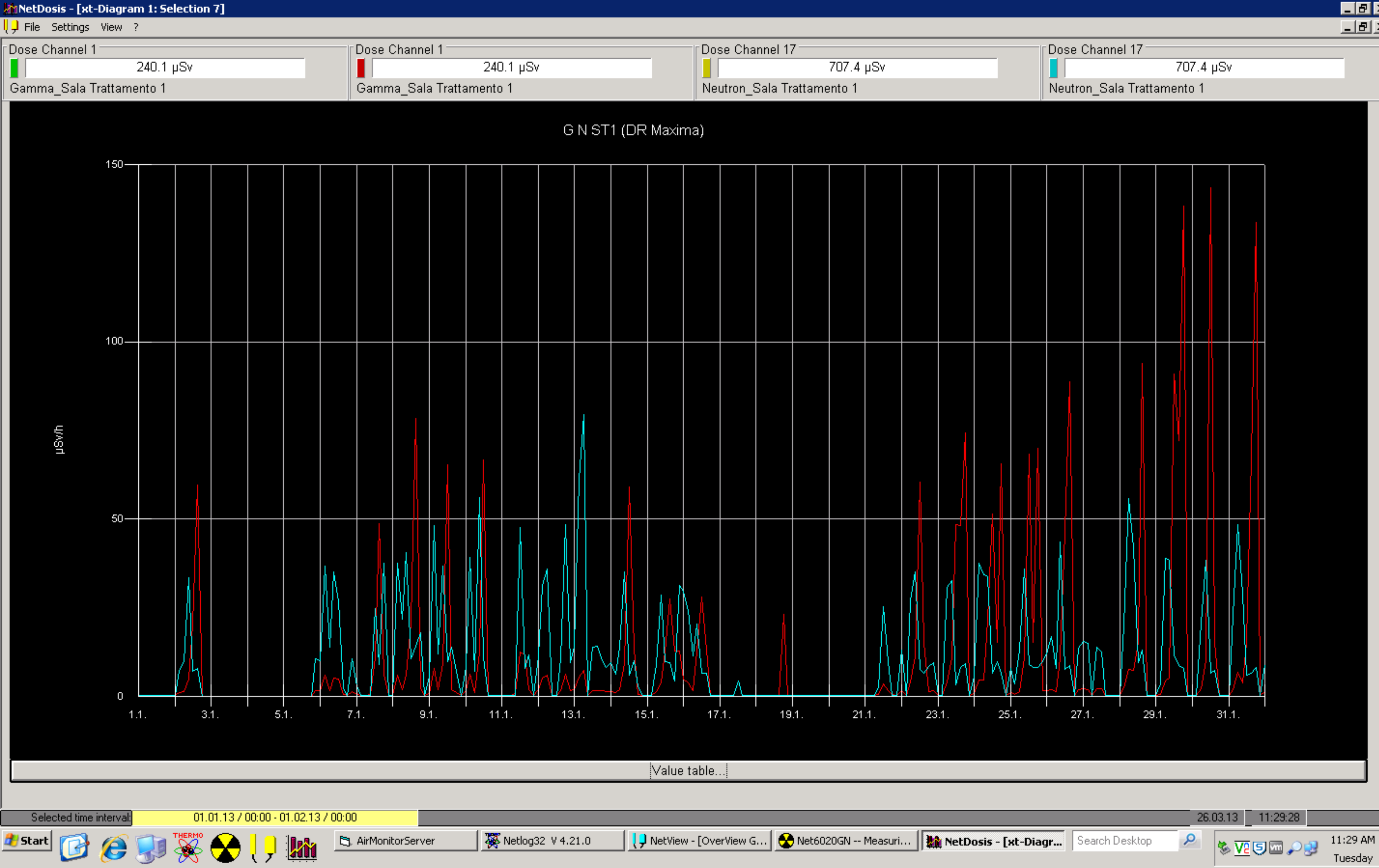
Search Desktop



They measurements are continuously available, real time



And they are logged, so that it’s possible to check the dose rates at any monitored location at any time.

There is also a net of passive detectors, in order to have a very detailed control of the radiation field all around the plant.

The net is made of photon dosemeters (TLD), and passive neutron extended range rem counters, based on CR39 coupled to a boron converter (that are read internally), with a lower detection limit of a few µSv over three months.

Because of the very peculiar radiation fields we have to deal with, many instruments have been developed internally (in the frame of a continuous cooperation with CERN, PoliMi and some industrial partners)

R&D ongoing

Need for:

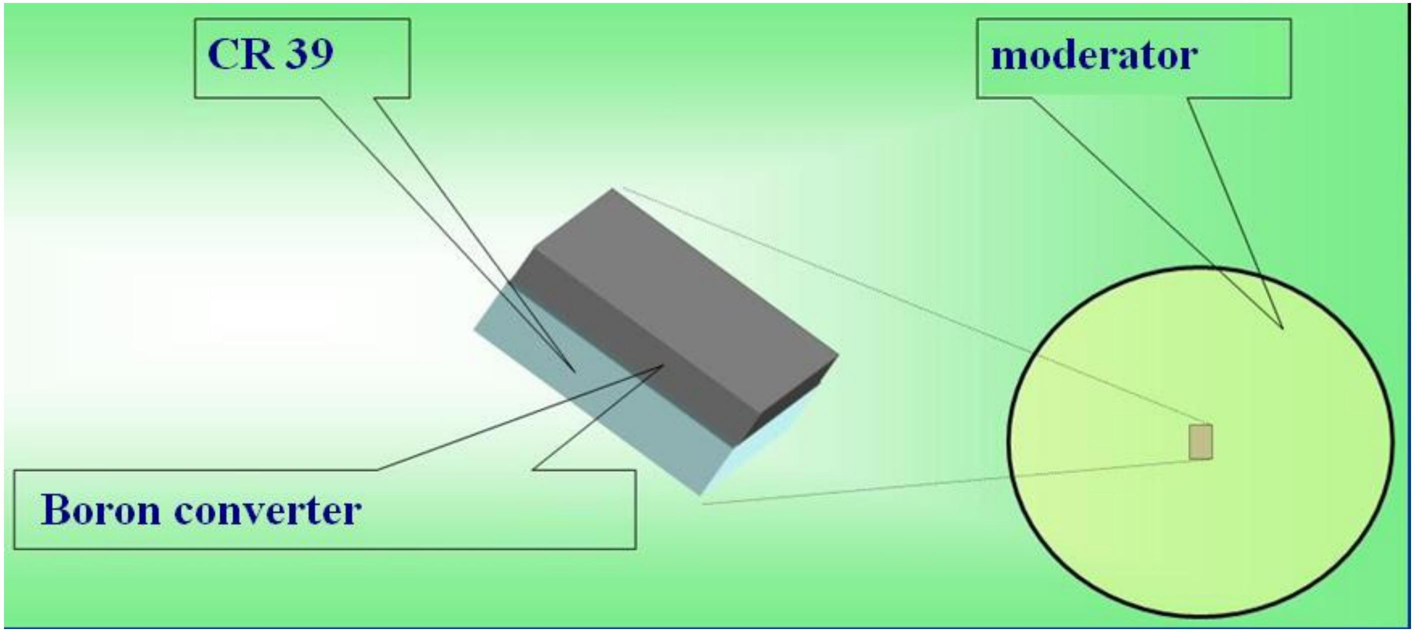
-Passive (⇔ inexpensive) area dosemeters able to monitor low dose rates integrated over a long time (es. 3 months), with LDL in the order of the cosmic background (few μSv).

-Passive dosemeters fit for personal dosimetry (low weight, reasonable LDL, wide energy range, able to detect high energy charged particles)

-Active area dosimeters able to work in pulsed fields, with a LDL in the order of the cosmic background.

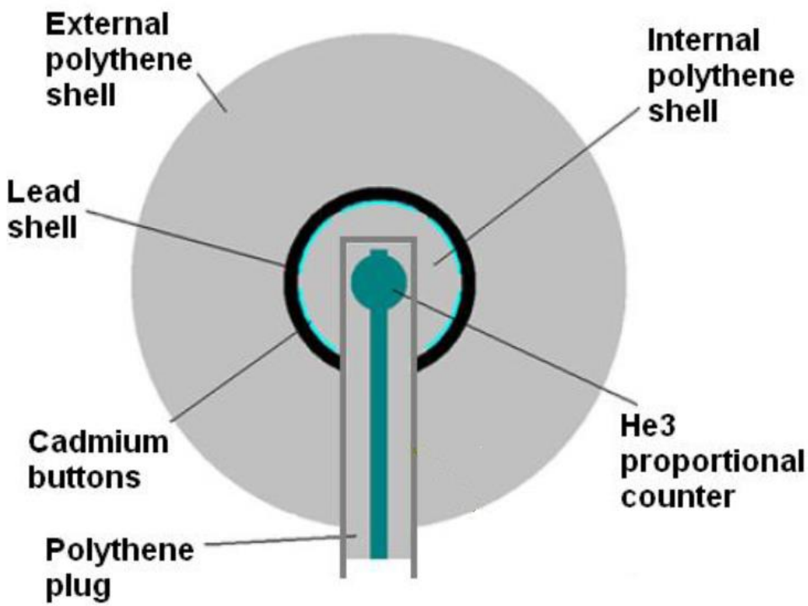
fondazione CNAO ⇔ POLITECNICO MILANO + research and industrial partners (CERN, PSI, AIT, MiAm, Else nuclear, etc…)

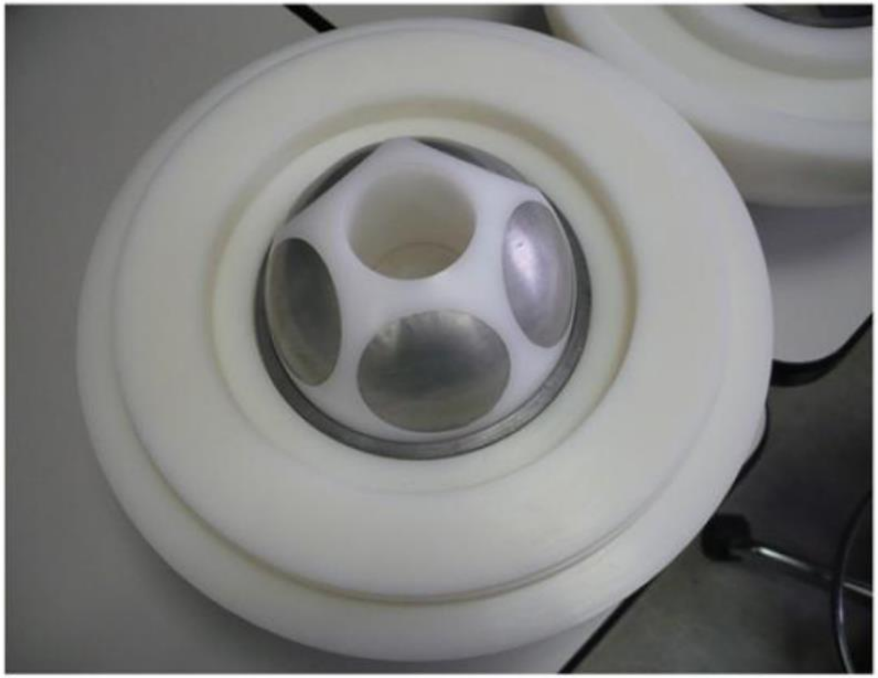
Passive rem counter



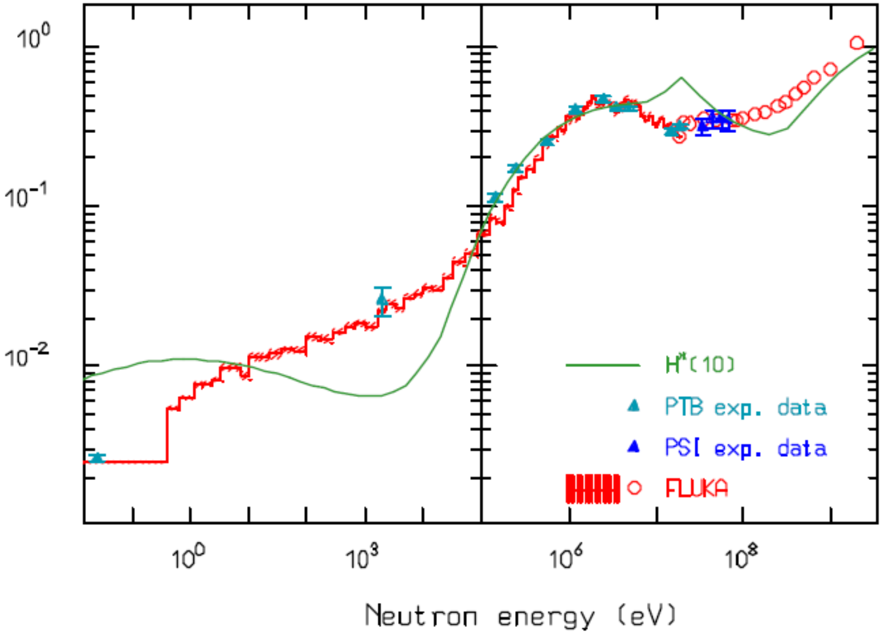
- The track detector is coupled to a boron converter, as thermal neutron detector (expoiting the n,α reaction on ^{10}B).

- The neutron is detected by the 1.47 MeV α particle. The number of tracks is proportional to the thermal neutron fluence at the center of the Rem counter





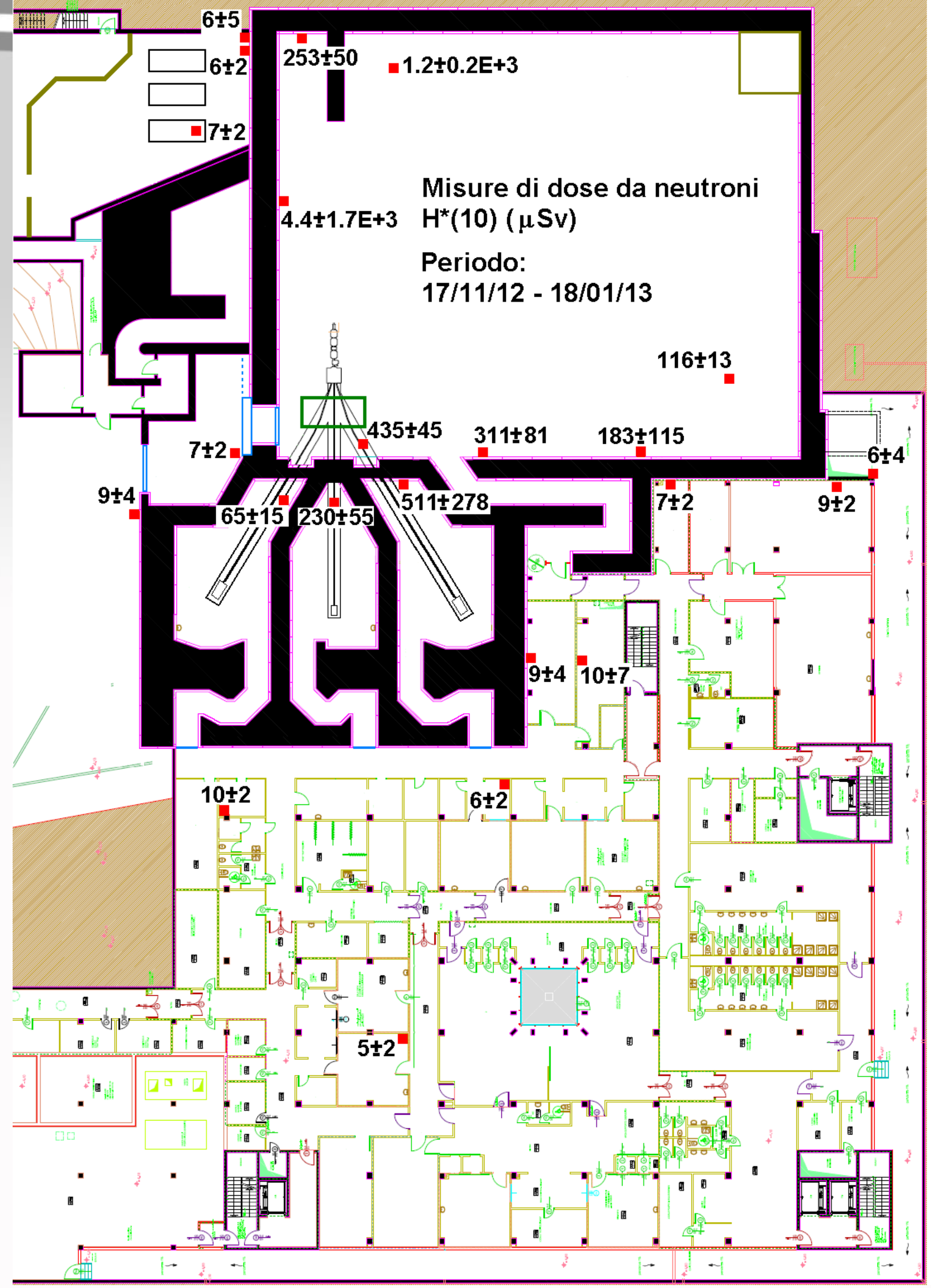
- 0,025 eV-1 GeV
- LDL ~ 3 µSv



It provides a cheap and reliable system for environmental neutron dosimetry

At CNAO a dense network of measuring points has been deployed

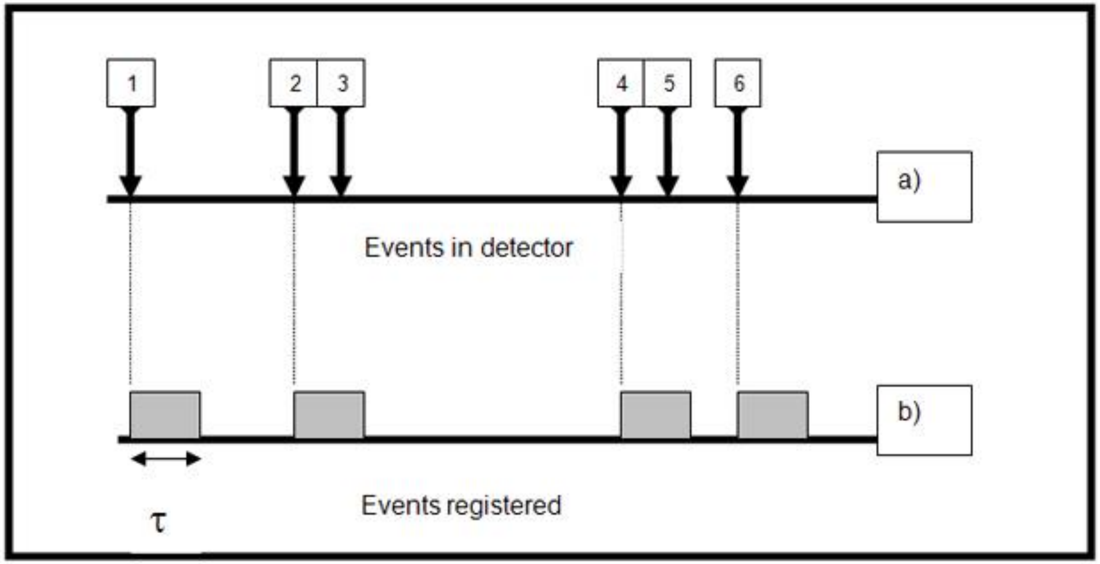
- The reading is independent from radiation field time structure (fine for pulsed fields, long integration time)
- Insensitive to gamma background
- Background is mostly independent on exposure time
- Low lower detection limit (down to 3 μSv)



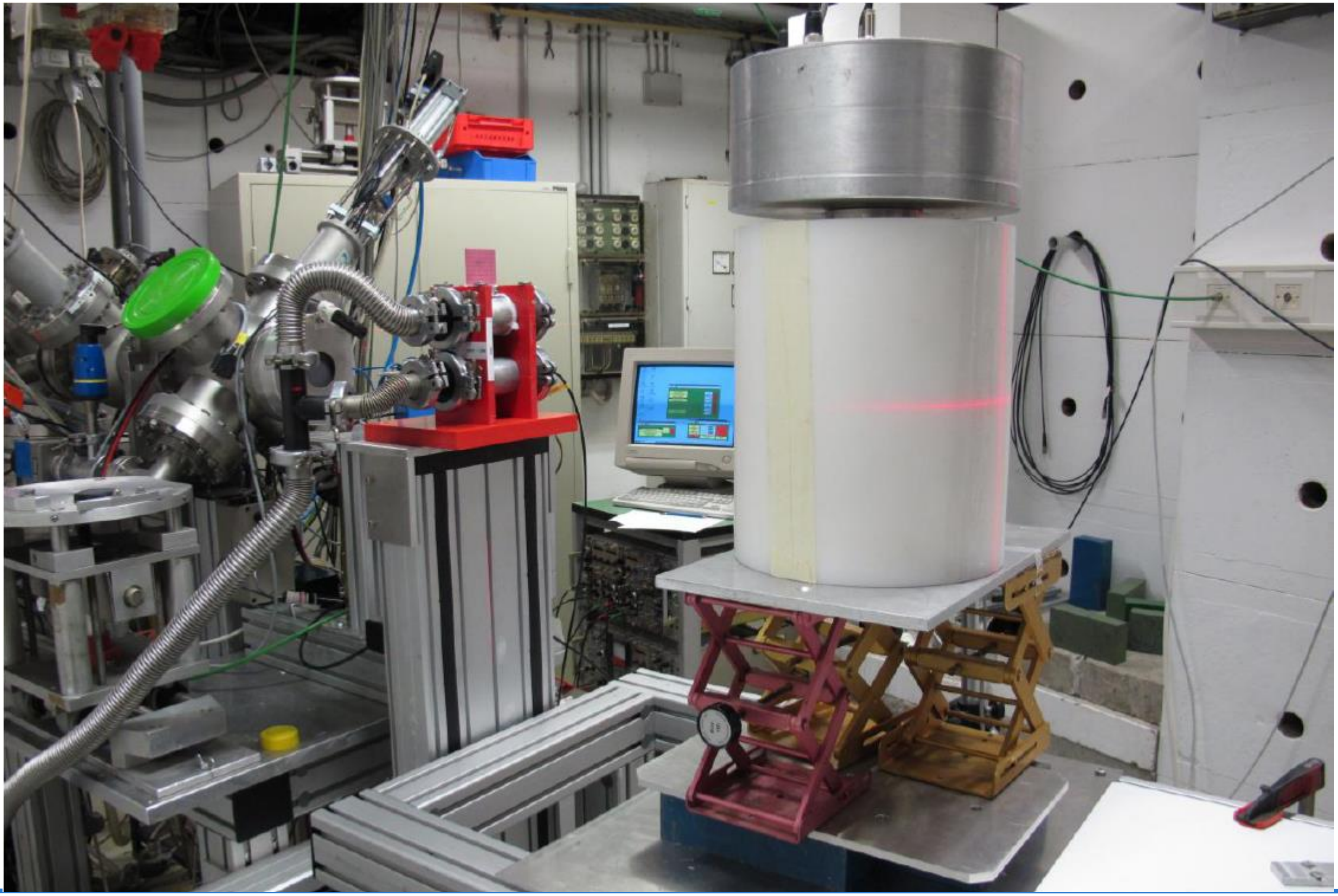
Saturation – pulsed fields

- Many accelerators are operated in pulsed mode ⇔the secondary radiation field is usually pulsed

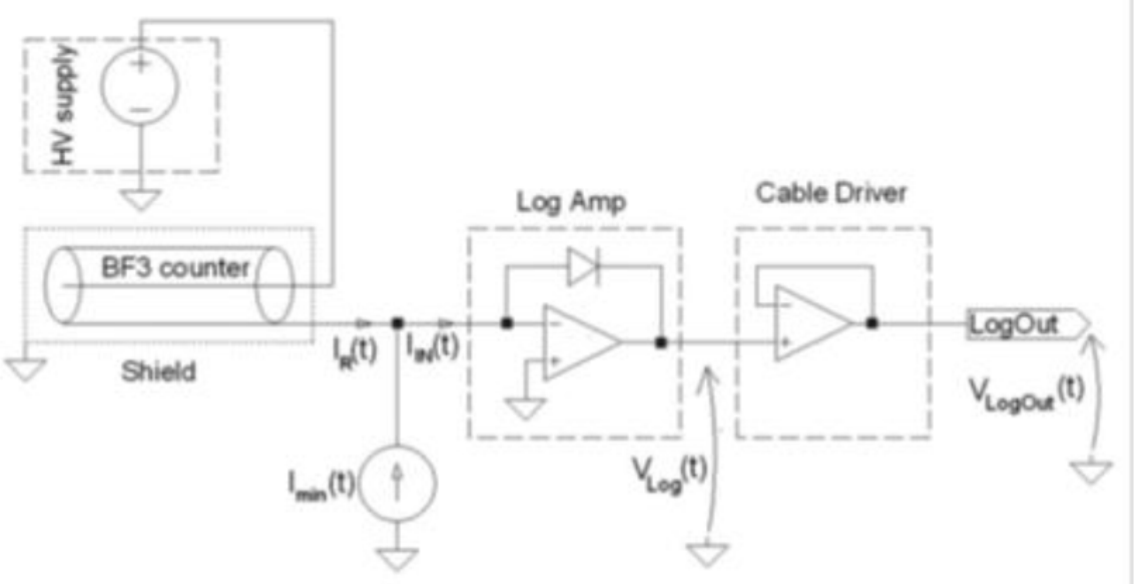
- Conventional neutron detectors (e.g. conventional rem counter used for area monitoring) suffer from saturation due to dead-time effects



LUPIN



LUPIN (Long interval Ultra wide dinamic Pile-up free Neutron detector)



The BF3 detector is placed inside a cylindrical polyethylene moderator with a diameter of 35 cm.

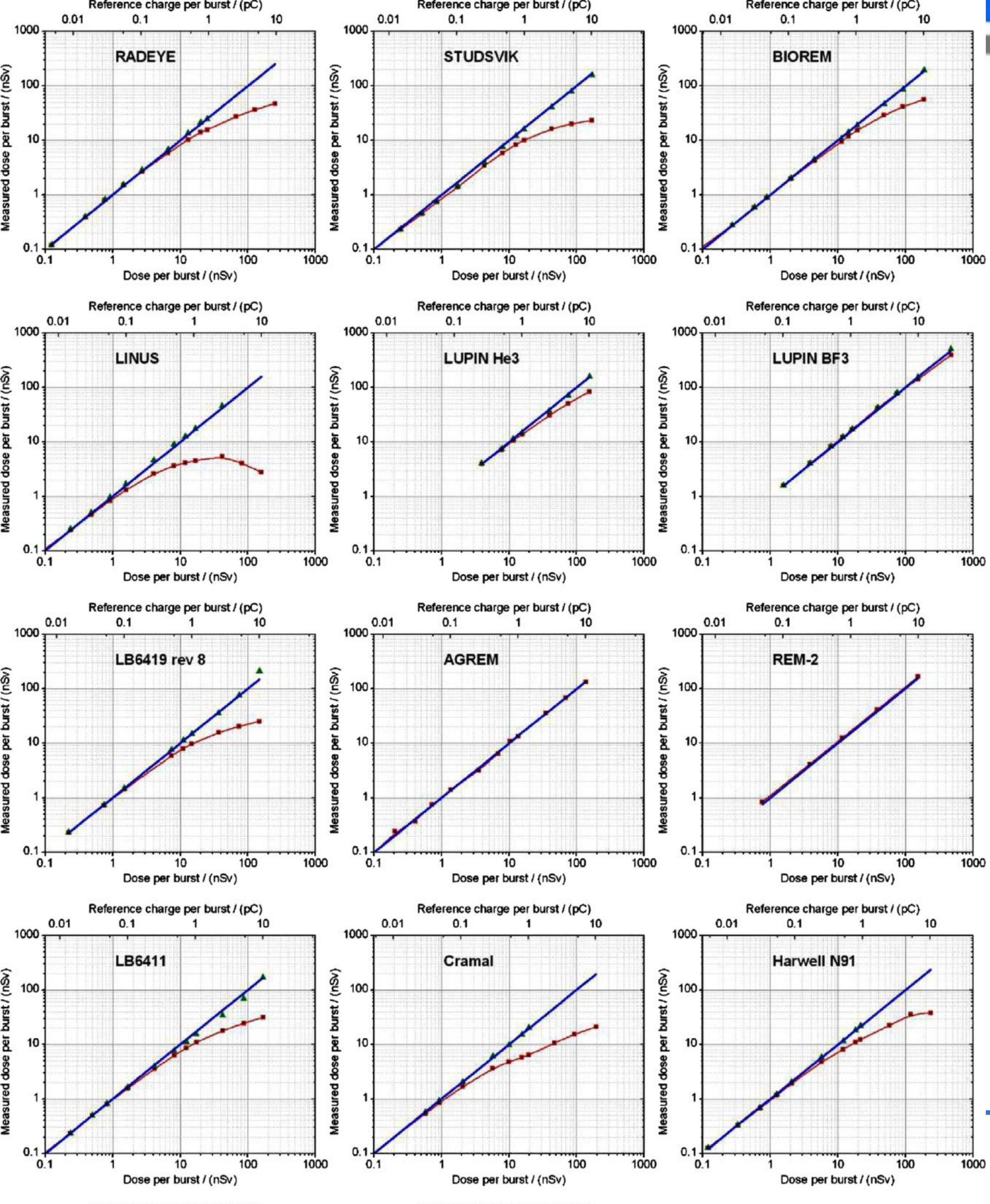
The signal LogOut is acquired with an ADC (12.5 MHz) and processed via software (current integration over a user settable timebase). The system measures the charge generated by a neutron interaction

- no dead time saturation
  (saturation due to other physical effects i.e. space-charge effects)

- Used inside a moderator, it can be used like a conventional proportional counter
  Has an “almost zero” instrumental background ⇔ it is able to detect the environmental cosmic neutron background

- It can be successfully used in pulsed neutron fields.

- It is sensitive to high intensity gamma fields (unless suppression algorythms are used)



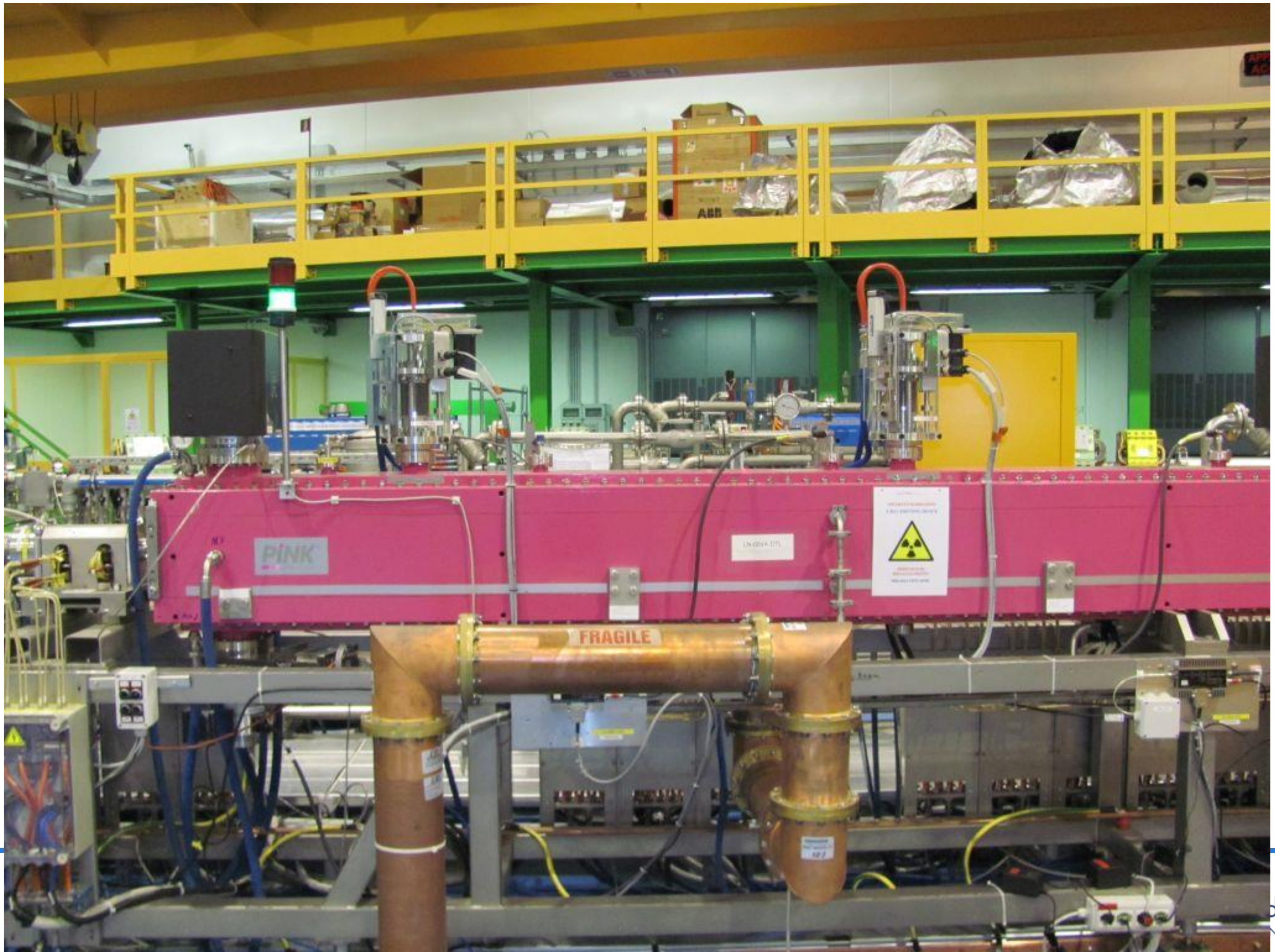
Measurements at @HZB

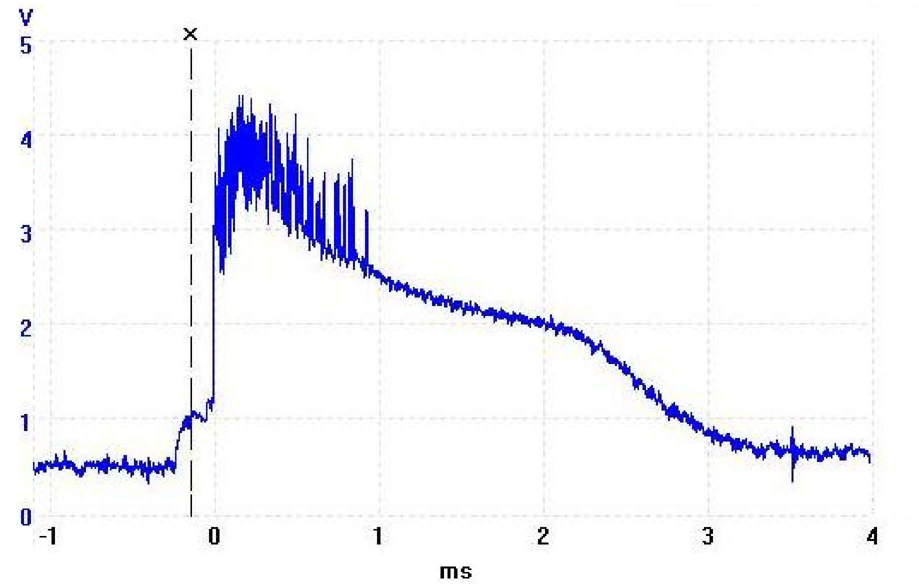
(2012 Eurados intercomparison)

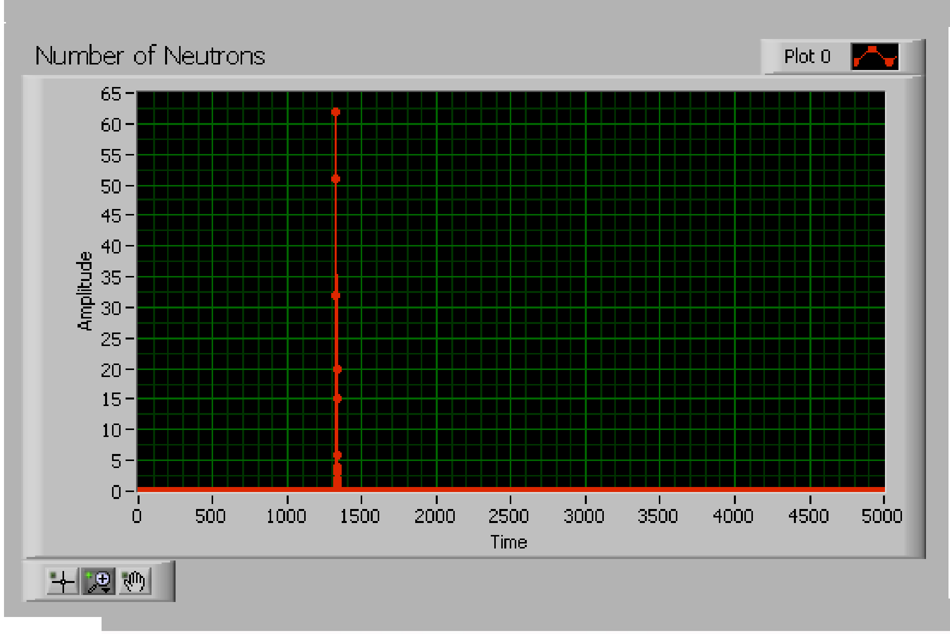
Caresana et al.
Intercomparison of radiation protection instrumentation in a pulsed neutron field
2013 NIMA Volume 737, 11 February 2014, Pages 203–213

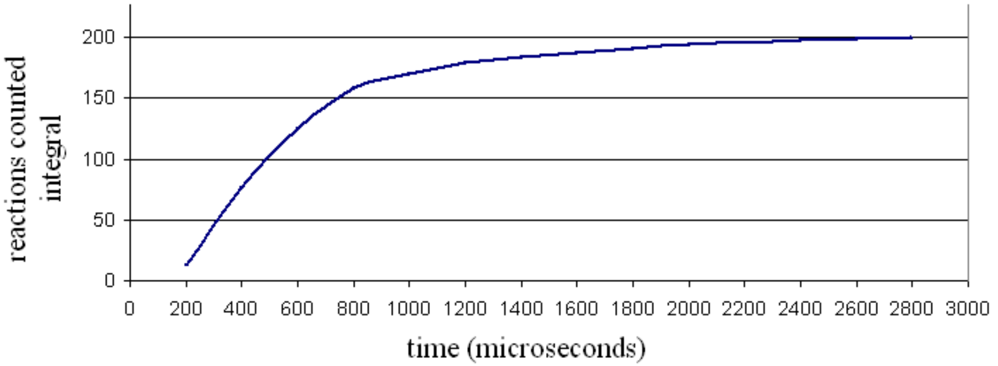
Measurements at CNAO

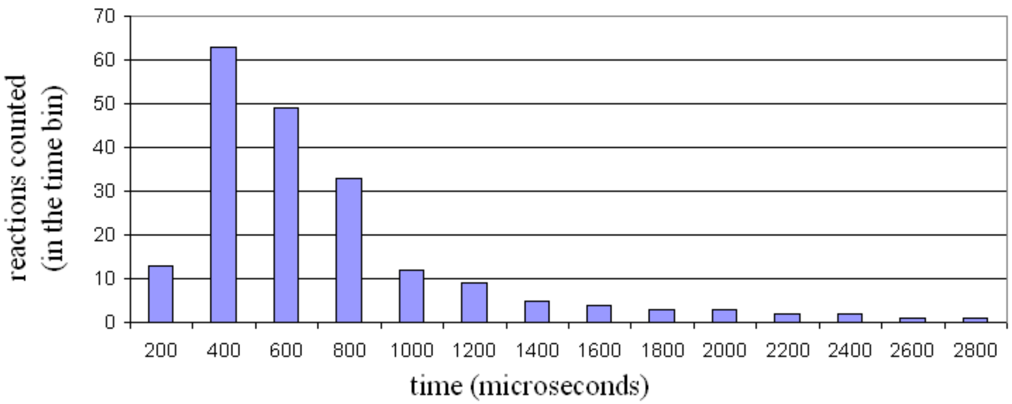
The linac is operated in a pulsed mode: a 50 ms (200 mA 7 MeV protons) bunch, every 5 seconds, is injected in the synchrotron, or dumped into a faraday cup.











CNAO Linac measurements: (neutrons due to 50 μs pulses: 7 MeV protons on a Cu target)

The charge is integrated on 200 μs bins

Additional problems also in pulsed mixed photon/neutron fields

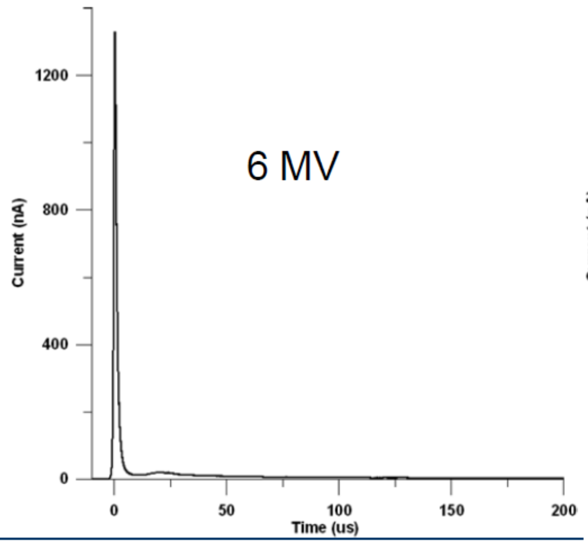
Measurement at S. Raffaele hospital

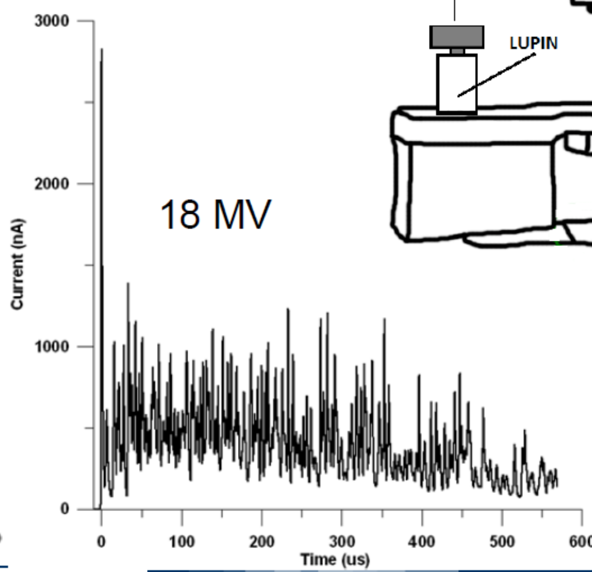
Electron radiotherapy LINAC: Varian Clinac® DHX - Dual energy

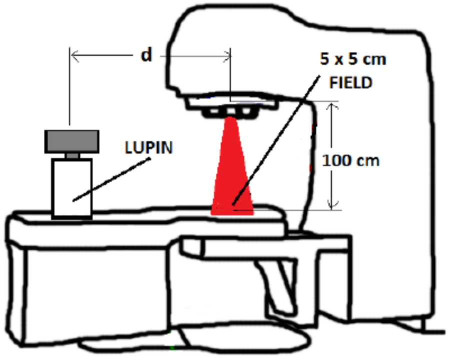
beam directed on the treatment couch, irradiation field of 5 x 5 cm^2.

The detector was placed on the therapy couch at 100 cm from the isocenter.

LINAC was operating 6 MV or 18 MV.







The mixed field problem

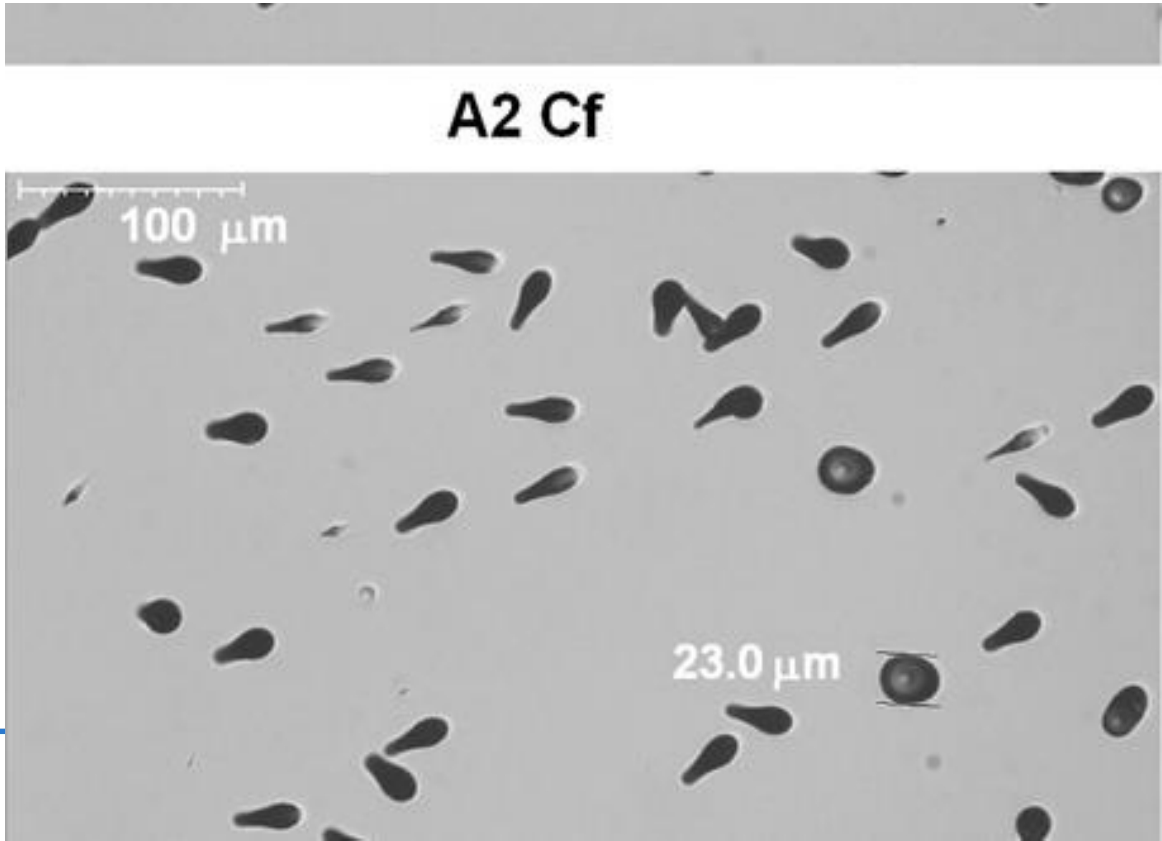
Outside the shielding, the main contribution to the ambient dose equivalent is due to the neutron component of the radiation field.

Inside the shielding, the dose due to secondary radiation is mainly due to charged particles.

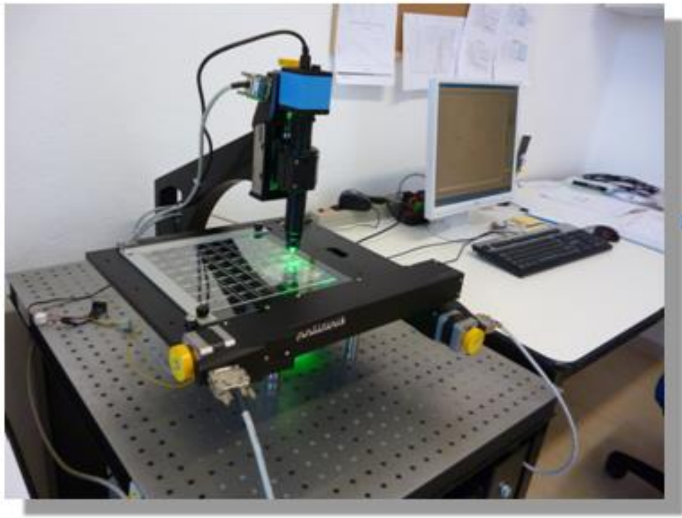
Personal dosimetry?

Neutron dosimetry based on LET spectrometry

Calculation of particle LET and impinging angle to get a direct estimate of the equivalent dose by estimating for any particle track the released dose and the quality factor Q(LET) .

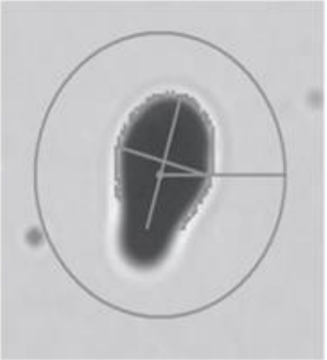


Track Analysis and LET determination



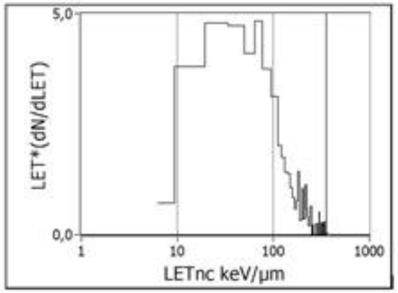
(a) Politrack™ SSNTD automatic reader

(b) Raw image captured with Politrack



(c) On line image analysis

(d) Measurement of D and d



(e) *LET* distribution (the suffix nc indicates that it is a quantity measured with Nuclear track detector CR39)

$$R = \frac{D}{2h}, \quad r = \frac{d}{2h} \tag{5}$$

By defining $K = V\sin\theta$ and carrying out some algebra, Eqs. (3) and (4) can be rewritten as follows:

$$K = \frac{1 + r^2}{1 - r^2} \tag{6}$$

$$V = \sqrt{1 + R^2(K - 1)^2} \tag{7}$$

$$\theta = \arcsin\frac{K}{V} \tag{8}$$

It is possible to calculate V and θ from the track parameters. LET= LET (V)

Assuming that n particles impinge on the unit area ($1\ \mathrm{cm}^2$), the dose (mGy) and the dose equivalent (mSv) can be calculated using

$$D = \frac{1}{\rho} \times 1.602 \times 10^{-6} \sum_{i=1}^{n} \frac{\overline{LET}_i}{\cos \vartheta_i} \qquad (2)$$

$$H = \frac{1}{\rho} \times 1.602 \times 10^{-6} \sum_{i=1}^{n} \frac{\overline{LET}_i}{\cos \vartheta_i} Q(\overline{LET}_i) \qquad (3)$$

where the $\overline{LET}$ is expressed in $\mathrm{keV}\ \mu\mathrm{m}^{-1}$, ρ is expressed in $\mathrm{g\ cm}^{-3}$ and $Q(\overline{LET})$ is the ICRP quality factor.

From LET and θ it is possible to calculate the dose and the dose equivalent.

If a 1 cm PMMA radiator is used, H is a good approximation of HP(10).

This is almost independent from the kind of impinging particle.

Energy calibration

Beam	Measured Dose (mSv)	Reference Dose(mSv)	Sensitivity
PTB 565 KeV	1.79	3.67	0.49
PTB 8 MeV	1.75	4.9	0.36
PTB 14 MeV	3.49	6.9	0.51
PTB 19 MeV	1.84	2.9	0.64
iThemba 66 MeV 0°	2.38	4.44	0.54
iThemba 66 MeV 16°	1.72	3.2	0.54
iThemba 100 MeV 0°	1.52	2.36	0.64
iThemba 100 MeV 16°	1.75	2.83	0.62

Flat response between 565 keV and 100 MeV

Repeatability

Detectors at CT 5	CHI²	Dose (H*10) in mSv	Detectors at CT 12	CHI²	Dose (H*10) in mSv
1810	1.03	1.93	1818	0.98	2.26
1811	1.00	1.98	1829	0.91	2.22
1839	1.07	2.34	1840	0.97	2.33
1846	1.05	2.11	1856	1.03	2.18
1850	0.96	2.28	1868	1.08	2.19
1855	0.95	1.82	1877	0.97	2.18
1871	0.92	2.05	1895	0.95	1.98
1893	0.97	1.86	1906	1.06	2.40
Mean Dose	2.07		Mean Dose	2.22	
St. Dev. %	8.9		St. Dev. %	5.6	
Ref. Dose	5.17		Ref. Dose	4.85	
Sensitivity	0.40		Sensitivity	0.46	

Measurements @CERF (simulated workplace field with a significant high energy neutron component)

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Thanks for your attention

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