A distributed network of sensors for real-time remote control of radioactivity and radiation

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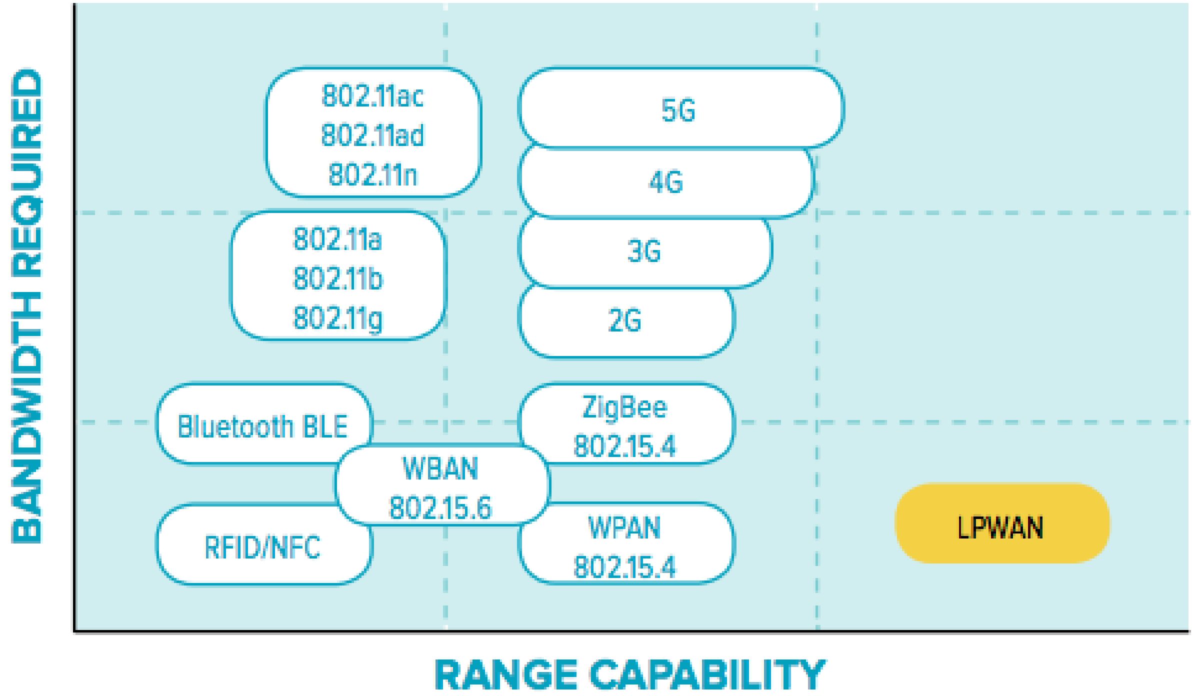
Main applications:
(source: INTEL)
Business/manufacturing 40.2%
Health care 30.3%
Retail 8.3%
Security 7.7%
Transportation 4.1%

IoT (source: Gartner, Inc):
8.4 billion things connected in 2017
30% increase from 2016
20 billions by 2020
5 million+ new things get connected every day
others (e.g. INTEL) put the figures 10 times higher



Low Power Wide Area Networks (LPWAN) as LoRa and Sigfox provide a practical way to transfer a limited amount of data over long distances with minimal power consumption. This solution is backed by massive investment in infrastructure by companies as Swisscom (in Switzerland).

Other solutions rely on 3G/4G and especially 5G in the near future

Key technology developments for IoT / radiation measurements:

- Affordable solid-state radiation sensors
- Reliable and cheap micro-controllers and memories
- New developments in wireless communication (i.e. LPWAN)
- Low power microelectronics
- Host of new low power devices (e.g. GPS, Bluetooth)
- Efficient batteries

Relevant new trends in IoT:

- Machine learning / AI integrated in IoT
- Big data
- New emphasis on security measures applied to IoT

Networks of radiation sensors for

- Environmental monitoring
  - ➡ Radiation monitoring of waste containers
- Radon monitoring

http://www.semtech.com/wireless-rf/internet-of-things/

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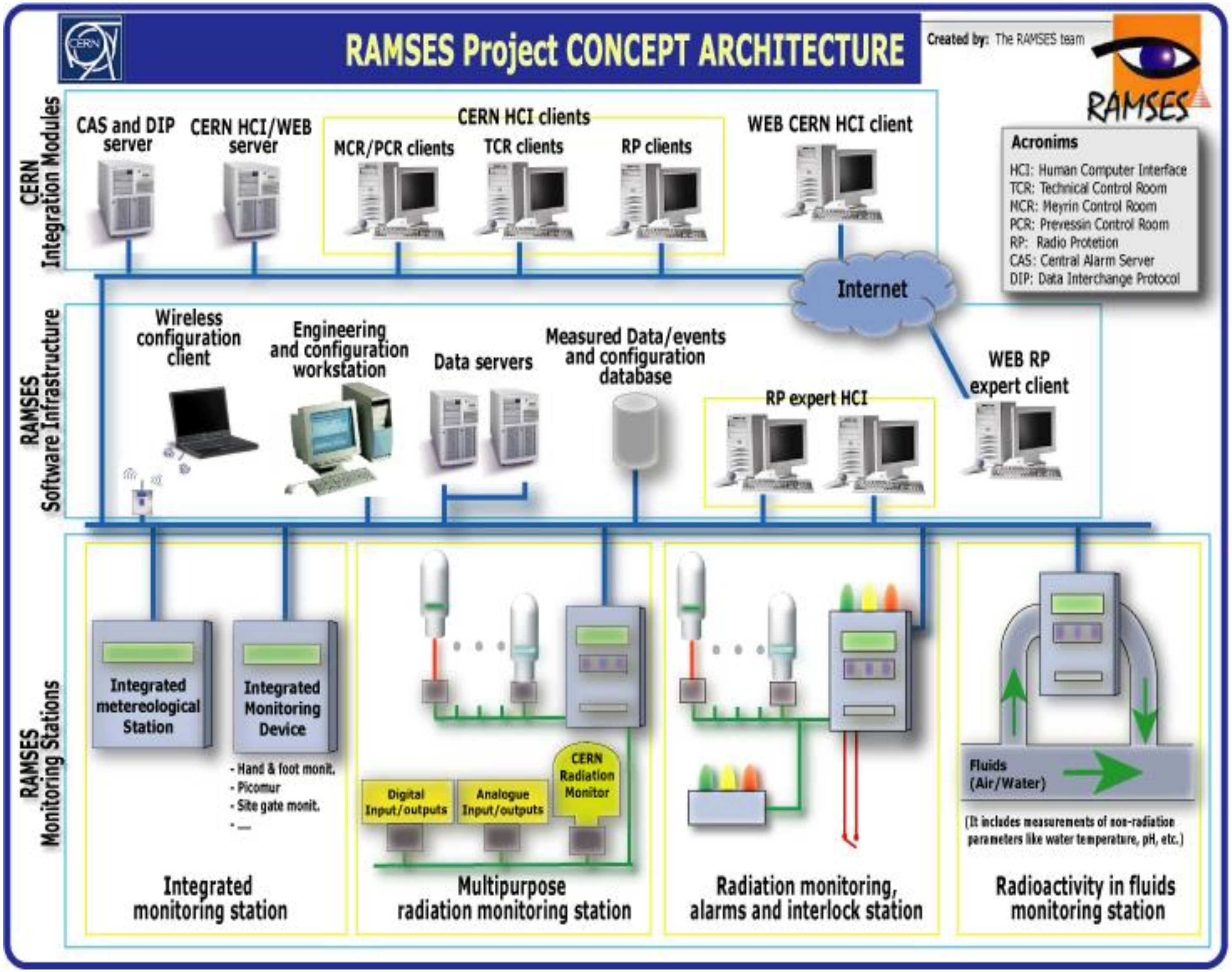
CERN radiation monitoring system (RAMSES)



The scope of the W-MON project

The radioactivity level of more than 100 metallic containers for ordinary waste is routinely monitored at CERN

- CERN Fire Brigade was in charge for many years
- Checking the waste containers twice per week overnight with an Exploranium GR110-G
- Now routinely performed by CERN Radiation Protection technical staff

1.5 x 1.5 x 2.0 inch (4.5 cubic inches) square cross section NaI (TI) detector

1. Human operator introduces variability/reliability issues
2. Exact inventory/location of containers must be known to the operator at all times
3. No automated data logging/alarm system
4. System blind between last control and emptying of the bin
5. Only just above 10% of all containers are controlled
6. Cost + CERN supervision

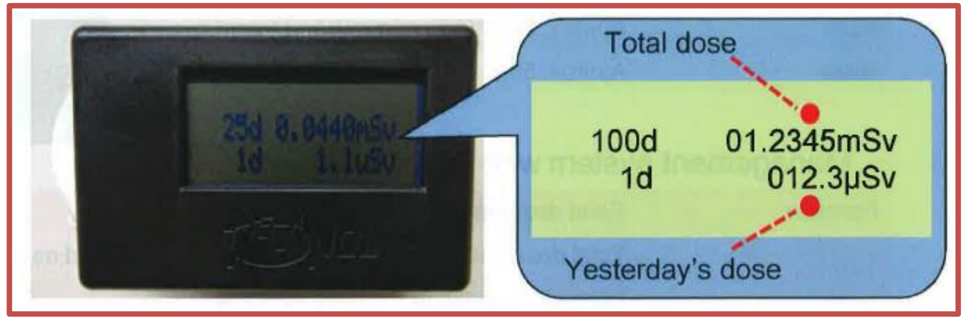
→ Upgrade to an automated system

Requirements for an automatic system

1. The radiation type to be monitored is mainly gamma rays
2. Sensitivity down to background level
3. Needs a robust device: resistant to adverse weather, temperature variations, vibrations and mechanical shock
4. Must operate unattended and with minimal maintenance
5. Low power consumption (battery powered)
6. Integrated data transmission facilities (e.g. GSM, WiFi, RF, LoRa sigfox)
7. Acceptable cost
8. To be connected to the existing RAMSES/REMUS system, which provides data logging and alarm functions
9. Relevant information: alarm for radiation level above threshold, alarm for equipment malfunctioning (auto-diagnostic), location of the container (GPS), log of the use of the container (whether the lid has been opened)

The D-shuttle personal dosimeter

D-shuttle personal dosimeter (silicon detector) from Chiyoda Technol



Personal reader

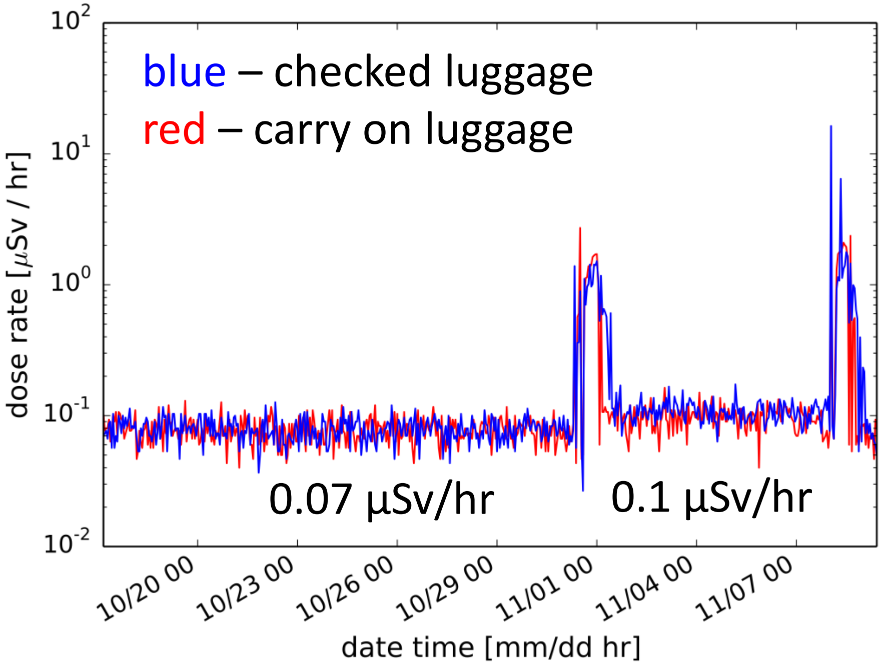
Workstation

Detector	Silicon semiconductor
Alarm	Flashing led indicating high dose rate
Memory	Record hourly dose
Lithium battery life	About one year
Display function	Total dose, days of operation, yesterday dose
Data mgmt. with PC	Read/reset dose, total dose, dose plot of last 24 hours and past one week; hourly, daily and monthly dose trend plot

How did I get to know the D-shuttle

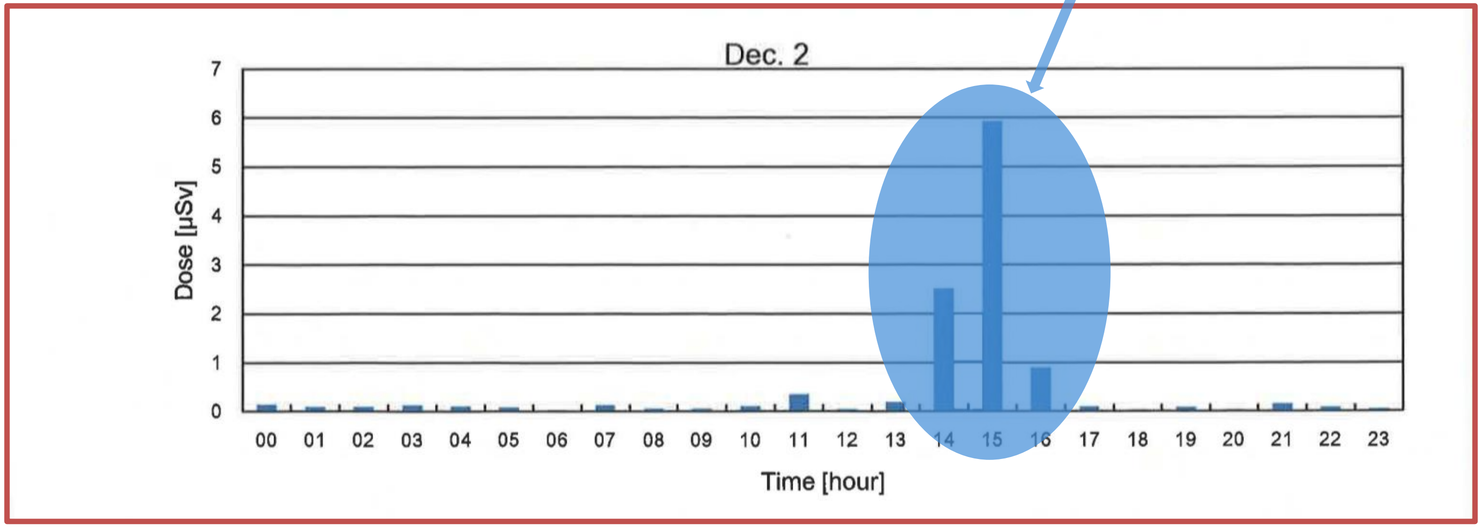
Visit of Fukushima NPP, December 2013

How did I get to know the D-shuttle

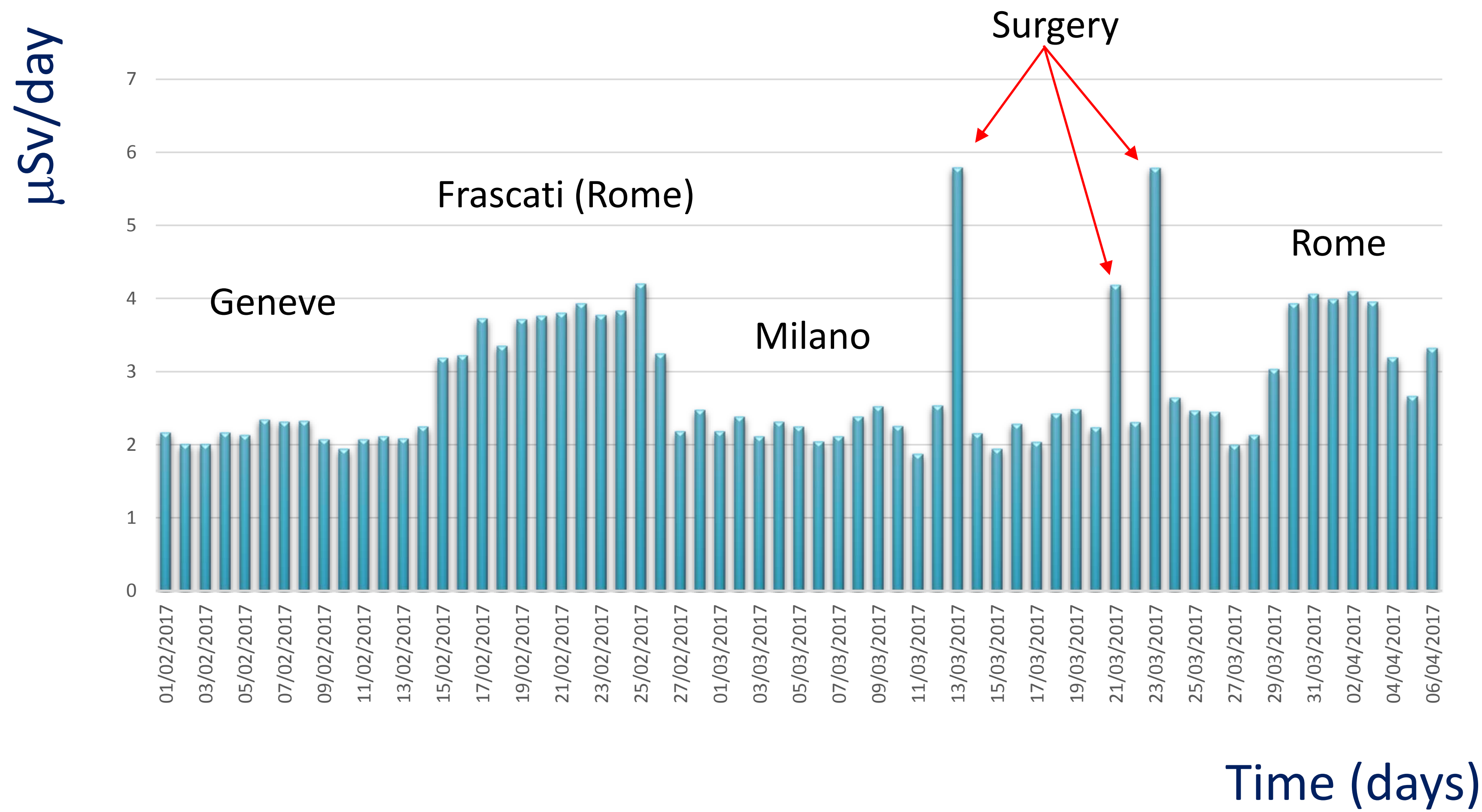


- ~ 14 µSv from San Diego to Geneva
- Looks like in San Diego the background radiation is slight higher than in Geneva 0.07 µSv/hr vs ~ 0.1 µSv/hr

Fukushima NPP visit
December 2013

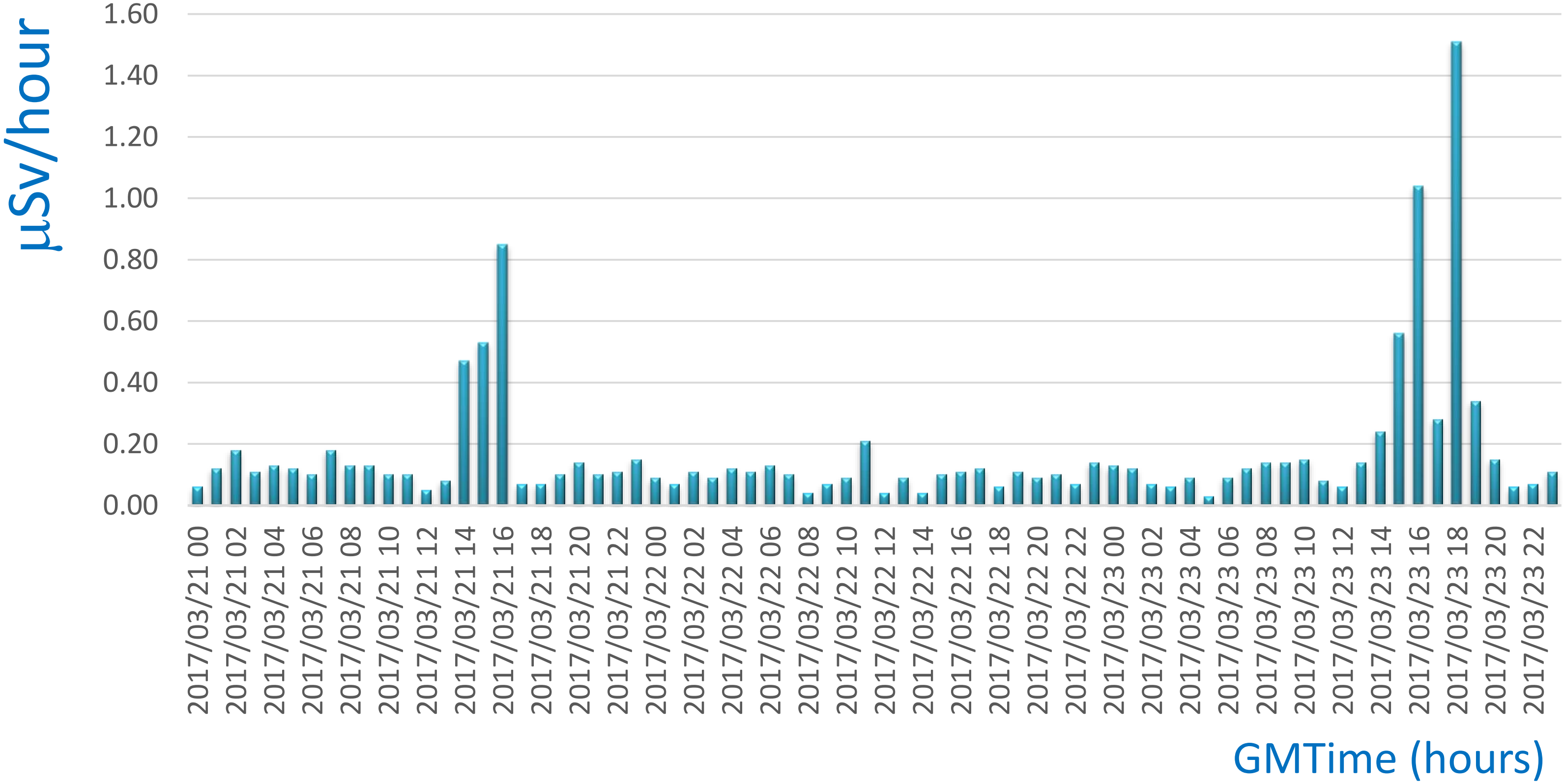


The natural radiation level in Frascati is 70% higher than in Milano or Geneva



D-shuttle measurement in hospital in March 2017

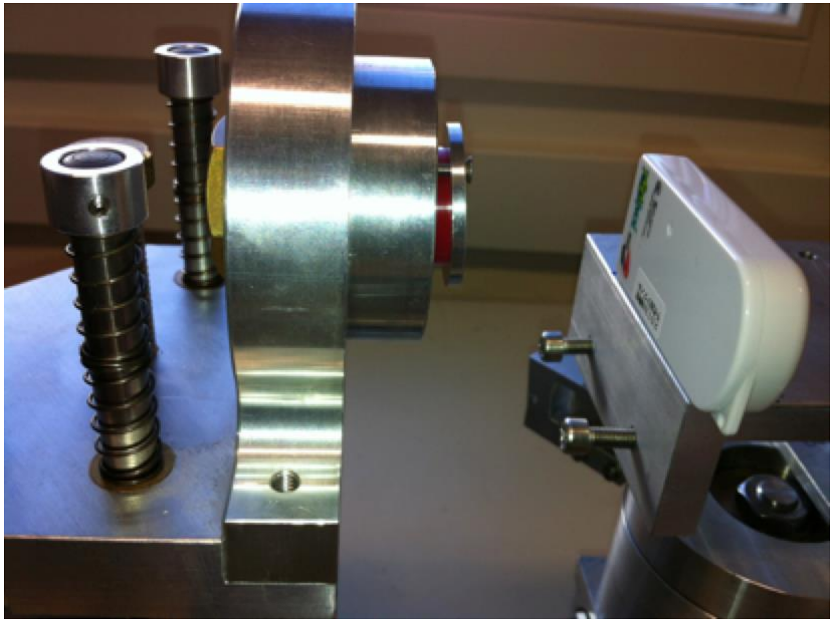
A ^{99}Tc-labelled radioactive tracer was injected in the patient: the D-shuttle was worn by a surgeon at the chest level without any particular protection (under the standard coat)

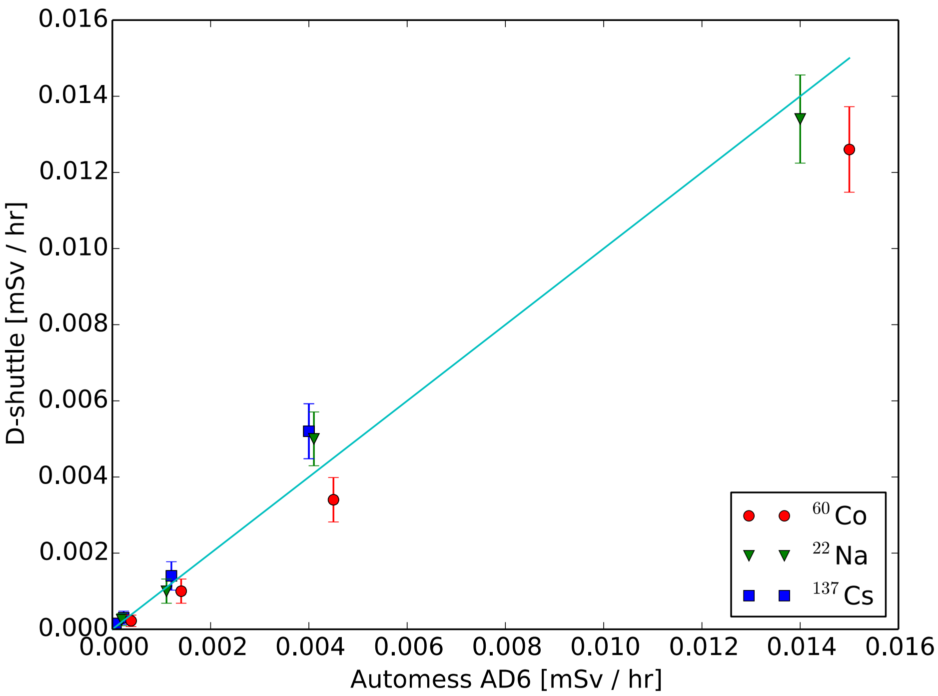


D-shuttle personal dosimeters from Chiyoda Technol

- Hamamatsu Si PIN diode
- Electronic board with microprocessor and memory storage
- “Mezzanine” communication board with optical and 2.4 GHz RF transmitters
- Shock sensor
- Lithium battery, lifetime 1 year
- Dose reading from 0.1 μSv to 100 mSv
- Size 68 mm x 32 mm x 14 mm
- Weight 23 g

Preliminary test of radiation sensors in a laboratory of the Radiation Protection Group with radioactive test sources (^{137}Cs, ^{60}Co, ^{22}Na)



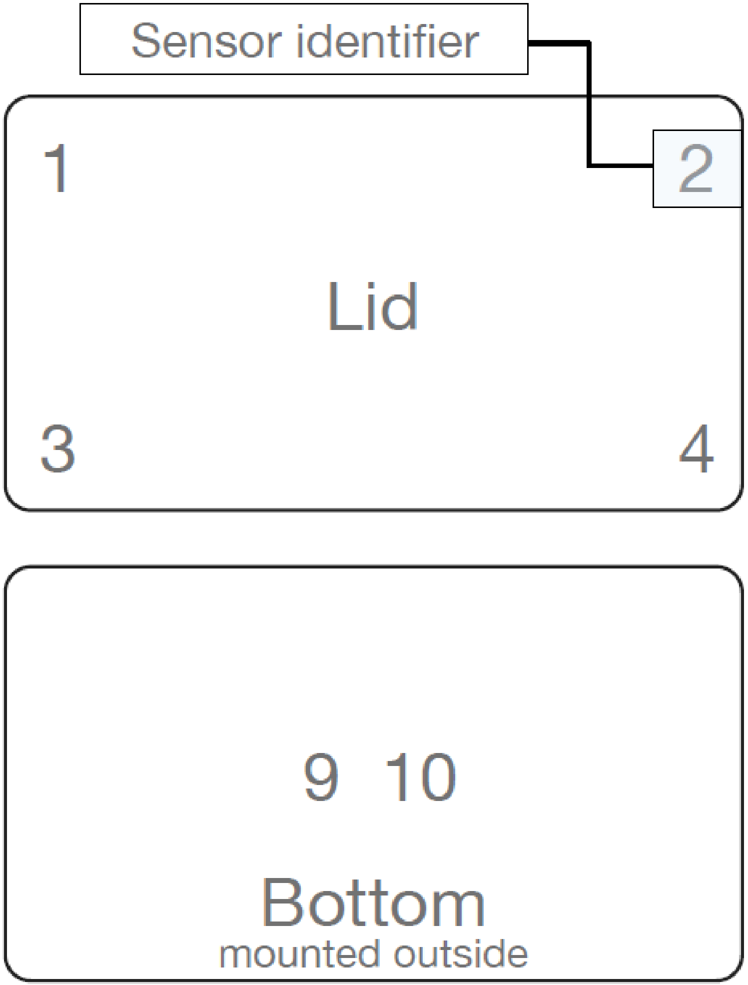


- Dose rate varied by changing the distance from the source
- The D-shuttle dosimeter shows a good linear behavior

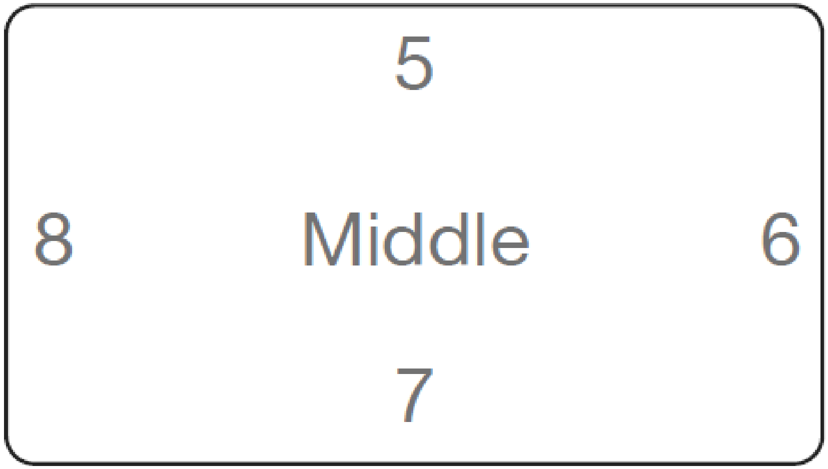
Test in operational conditions

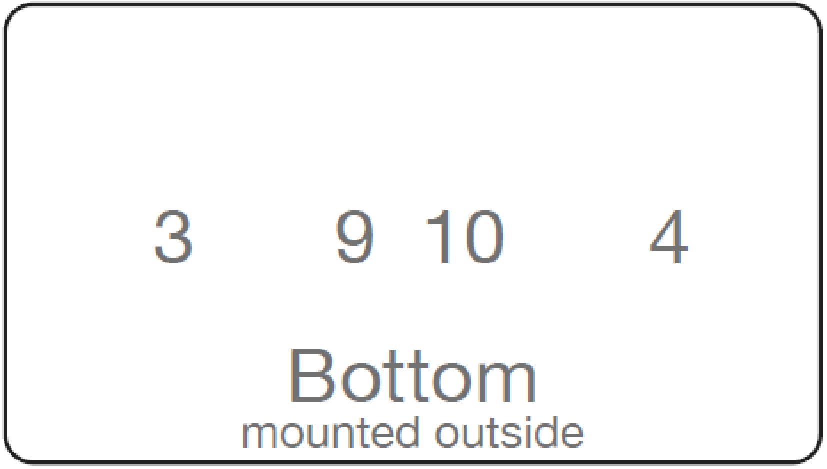
- “Realistic” test with a standard container for metallic waste and real CERN radioactive waste (slightly radioactive copper cables)
- 10 D-shuttle sensors provided by Chiyoda
- Readout provides hourly information but we needed a Japanese “interface” (help from Dr. Takubo Yosuke @ CERN)
- Performed over one week in March 2014
- 9 radioactive pieces dumped in the waste container over a week:
  - for each piece, dose rate measured in contact and on the four sides of the waste container

Test in operational conditions: sensor coverage



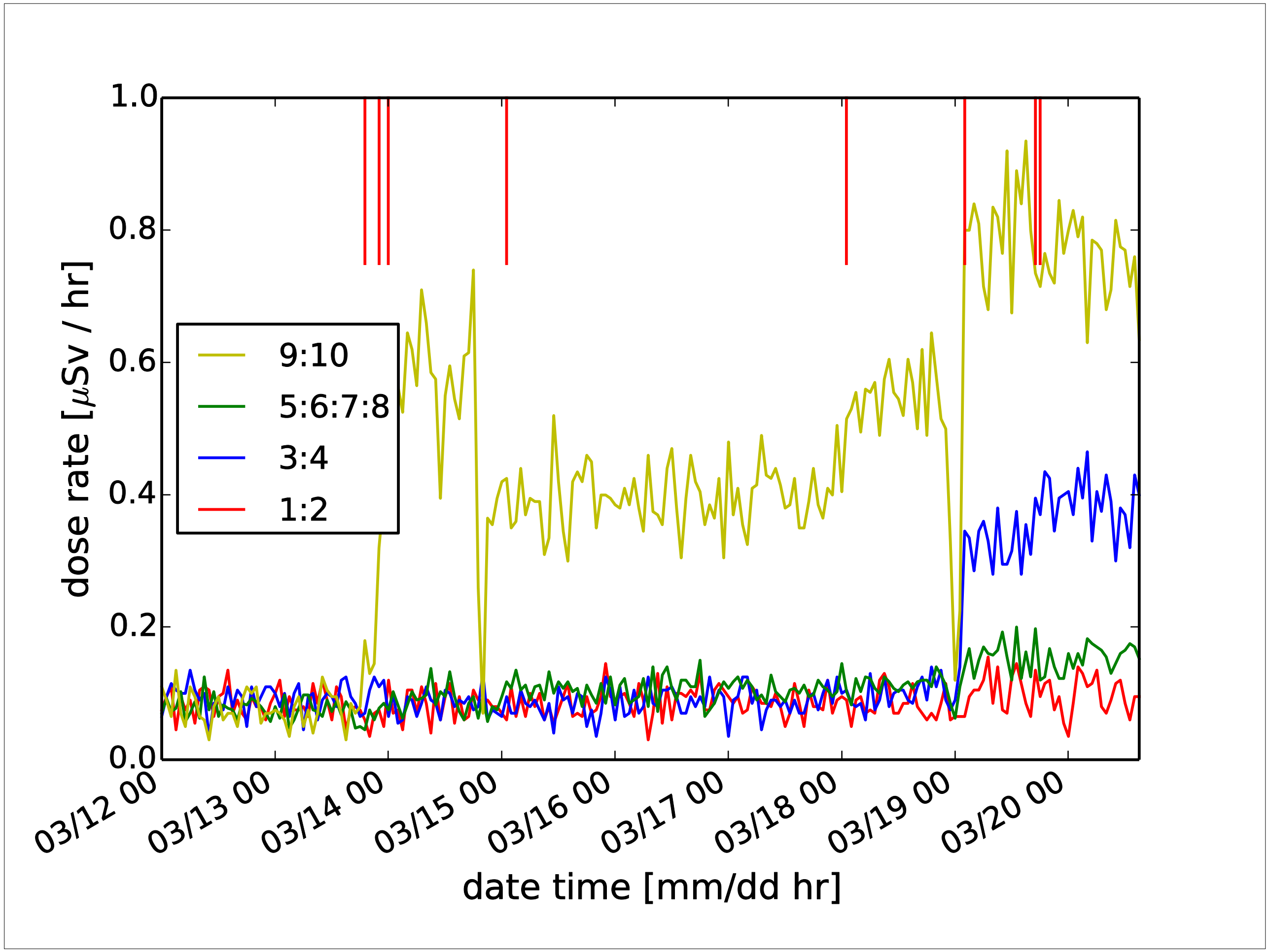

1
2
Lid


5
8
Middle
6
7


3
9
10
4
Bottom
mounted outside


非売品
非売品

Test in operational conditions



- Filling the waste container from the bottom
- The 2 dips are due to reading of the sensors [taken out for ~2 hours]
- The lower reading after #4 went in is due to the pieces rolling toward the sides

Test in operational conditions: conclusions

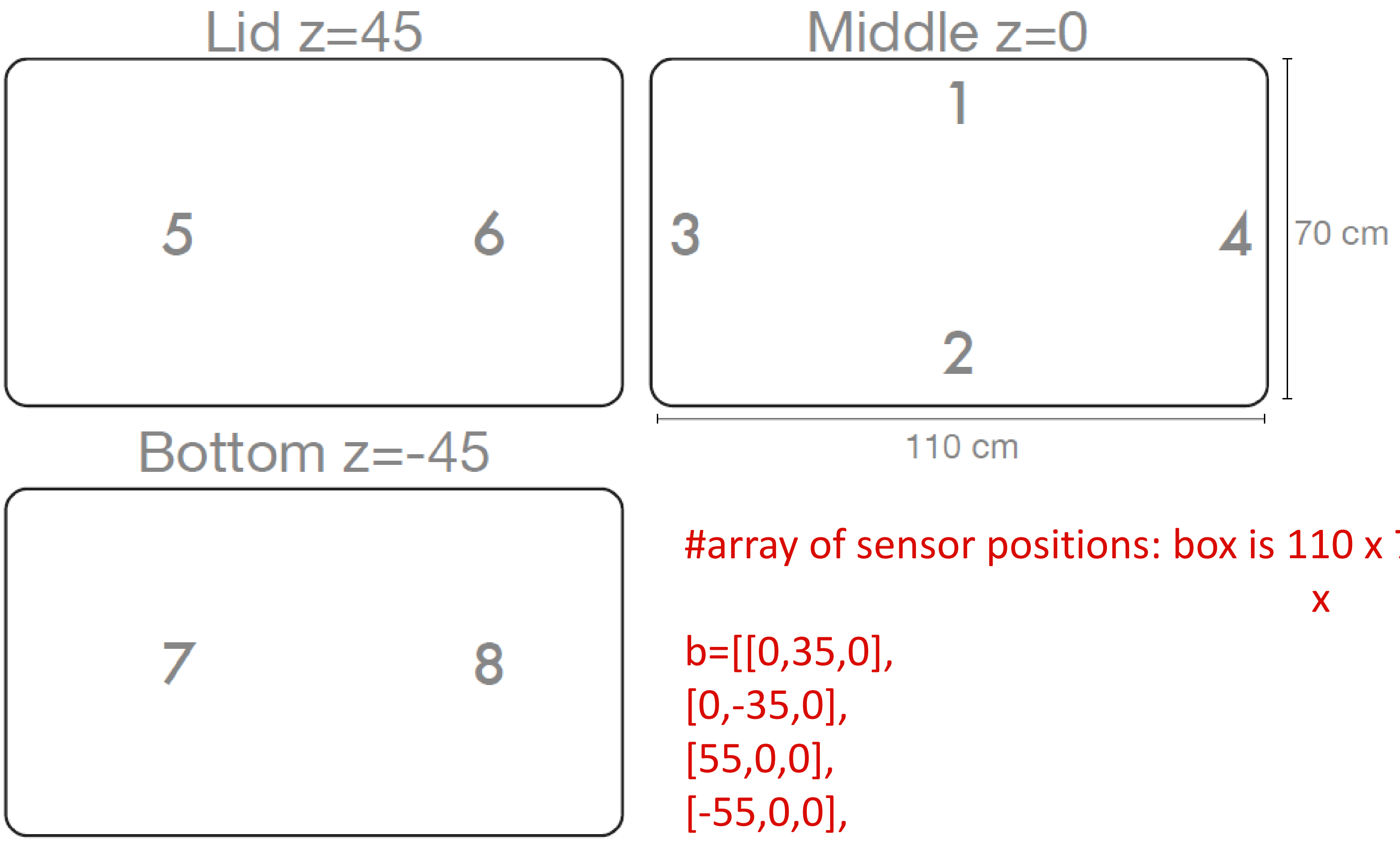
- The sensitivity is dominated by geometry (as expected): since filling from the bottom, sensors at the bottom are the most sensitive
- With the sensors in the middle we saw increased activity anyway
- Nothing is seen on the lid, where the dose rate is within 20% of background at all times, because radioactive samples were too far
- With the Exploranium [after piece #5 was put in] measured less than a factor of 2 over background → the waste container would not have triggered an alarm with the current procedure
- All 10 sensors worked well during the test

Further optimization: software simulation

- Decide minimum number of sensors and optimized configuration providing the needed sensitivity
- Sensor: modelled on the Chiyoda D-shuttle, which gives 10 counts per 0.1 μSv (= 10 cts/h per 0.1 μSv/h) with ^{137}Cs source photons
- Place **n** of them around a box the size of a standard waste container (110 x 70 x 90 cm^3)
- For a given point inside the box, calculate the distance from the sensors [**n**-D array] and get the minimum

- Python code performing the geometrical calculation, plus modeling of the sensor [basically including Poisson fluctuations]
- Input for **n** sensors: **n**-D array of 3 vectors with [x,y,z] of each sensor. [0,0,0] at the center of the box
- Map the volume in steps of 5 cm along each coordinate and calculate distance to each sensor
- Now the dose rate (or related quantities) can be calculated for a point-like source inside the empty box

Geometry: example with n=8



#array of sensor positions: box is 110 x 70 x 90 cm^3

x y height

b=[[0,35,0],
[0,-35,0],
[55,0,0],
[-55,0,0],
[30,0,45],
[-30,0,45],
[30,0,-45],
[-30,0,-45]]

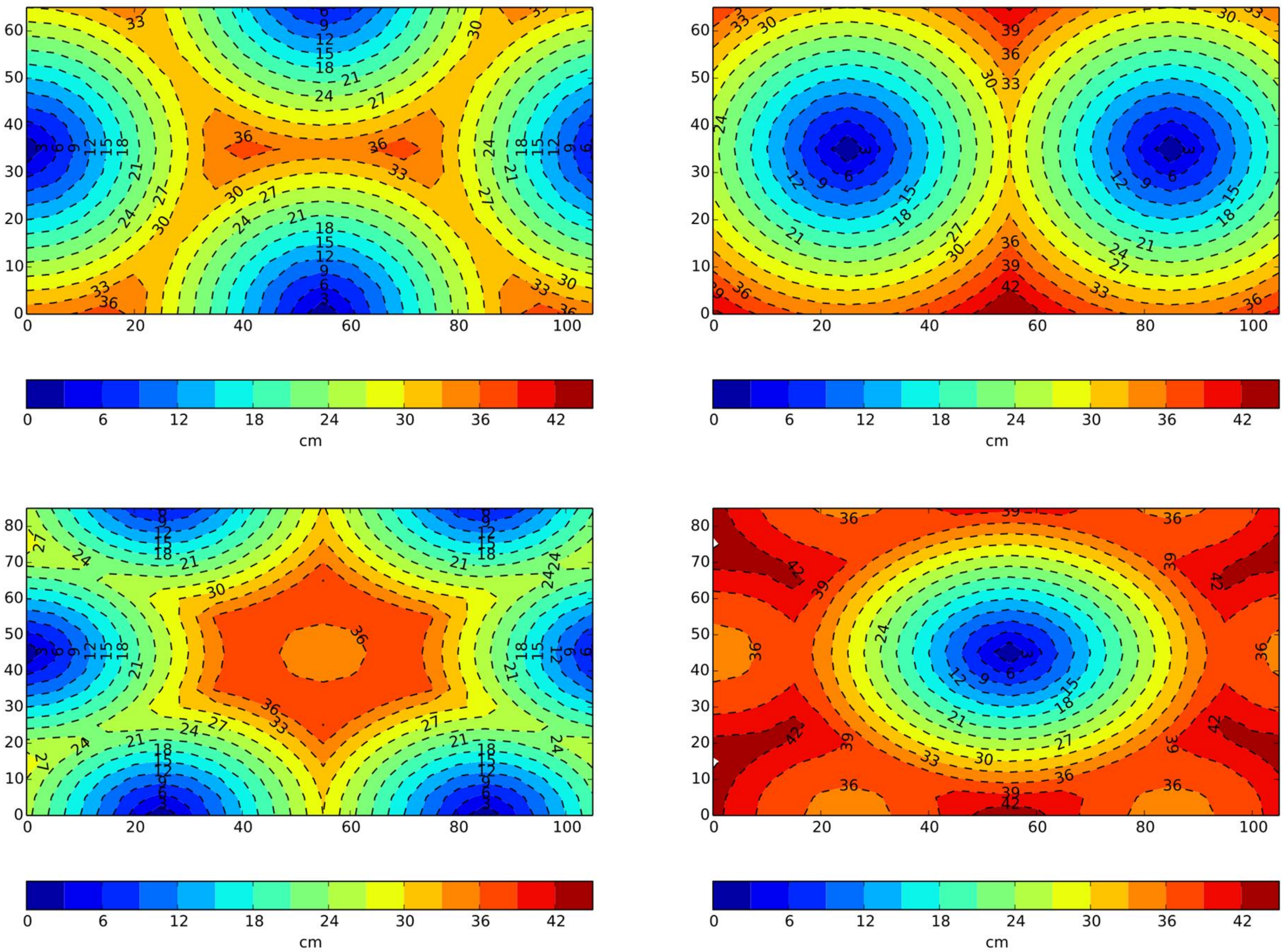
Some (closest sensor) distance maps

Horizontal Mid-plane

Top or bottom

Vertical Mid-plane

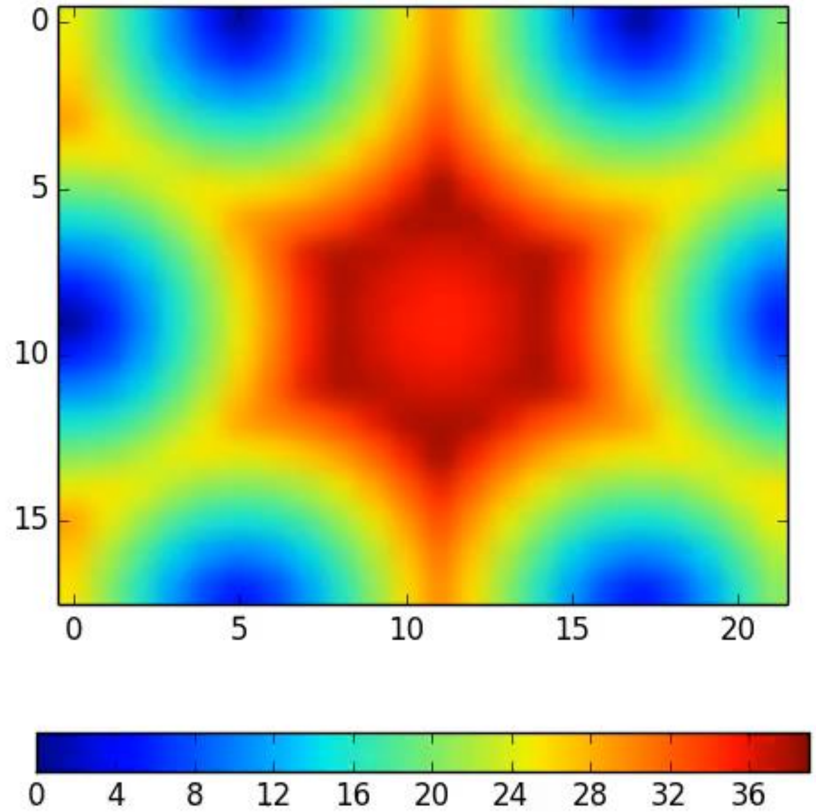
Side



Distance map: distance of closest sensor at any given position (in cm)

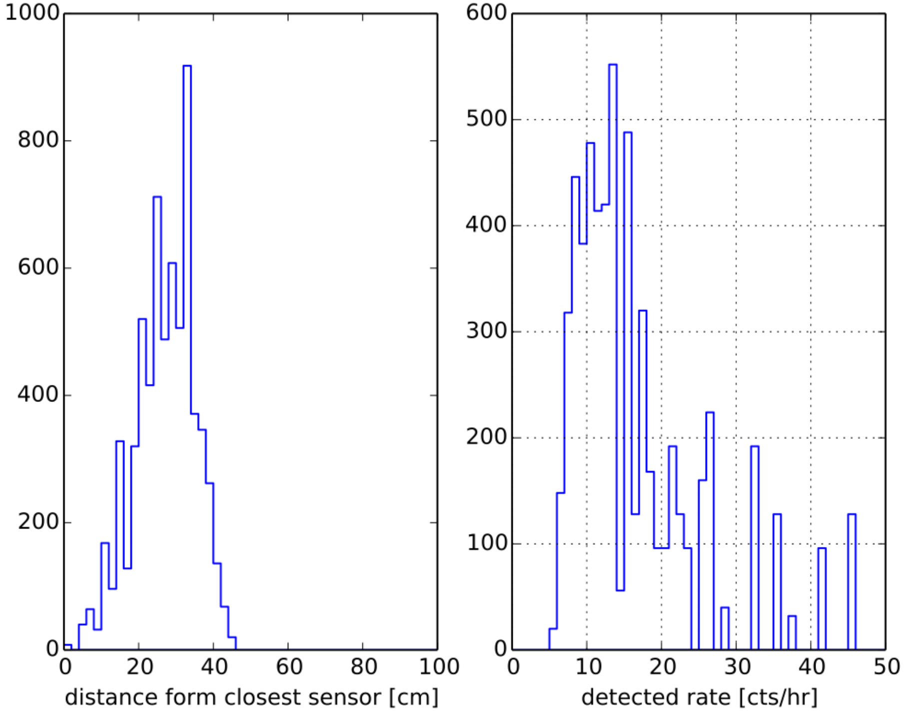
Some (closest sensor) distance maps

Distance map in 5 cm steps

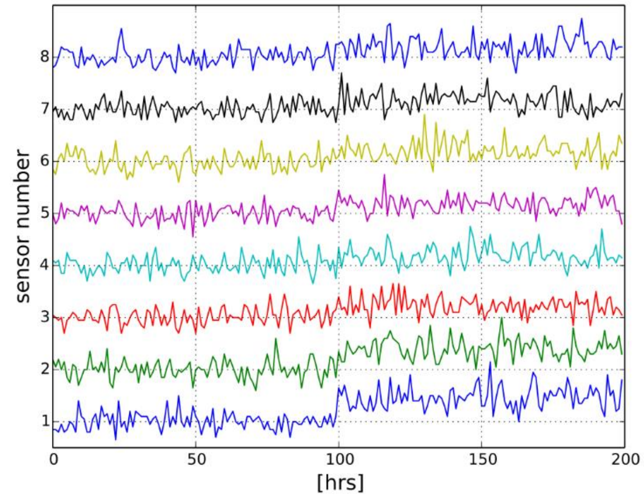


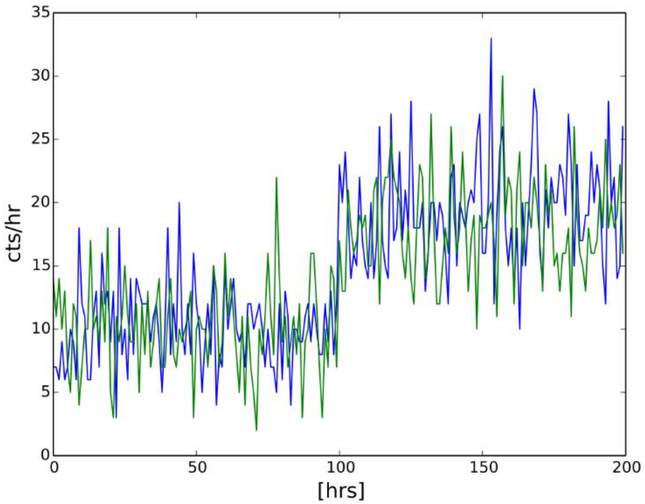
Results

150 kBq ^{137}Cs source
in the centre of the container



Mean 25 cm





Background would be 10 cts/h

8 sensors, source on the bottom at [55,0,-45]

Test in operational conditions

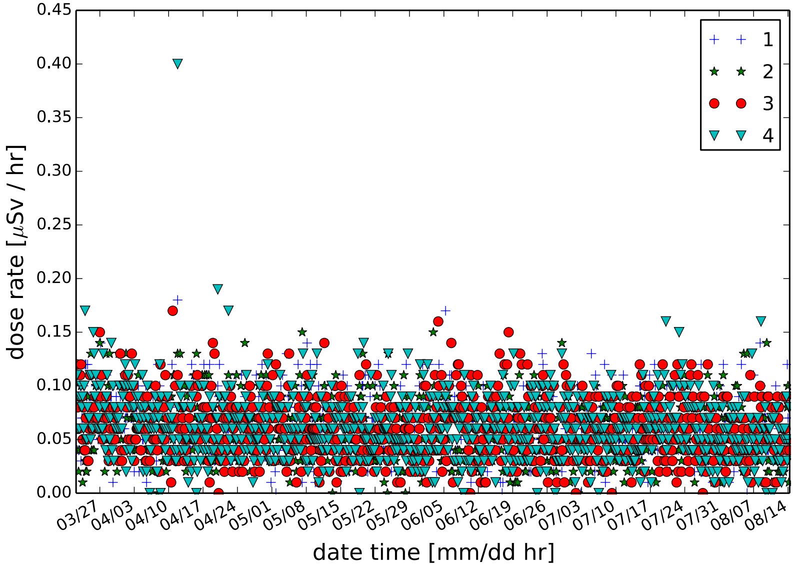
Various tests performed:

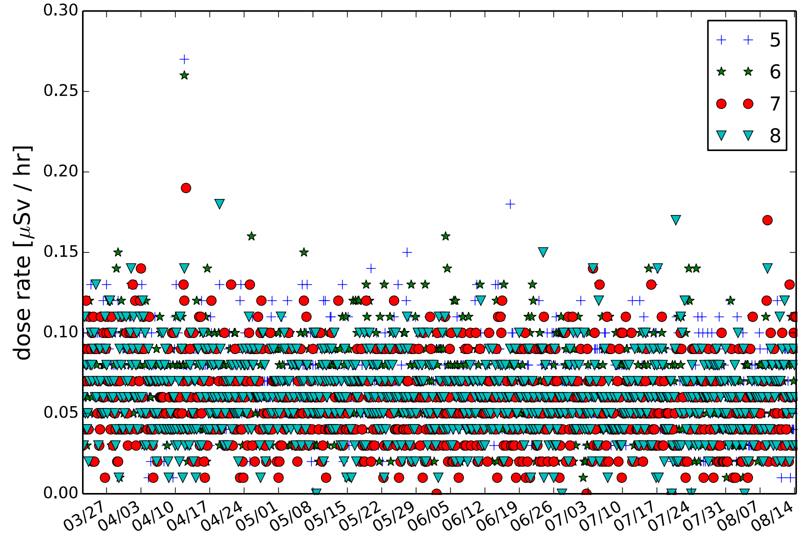
- ✓ Temperature stability
- ✓ First month-long outdoor test
- ✓ Shaking test (in a washing machine!)
- ✓ All tests OK!
- ✓ Data taken with neutrons [CERN calibration laboratory], in a mixed field [CERF], at altitude when traveling to US, Japan and Italy
- ✓ Operational test in realistic conditions on a container equipped with 8 sensors, manual reading. Ongoing since April 3rd

Test in operational conditions

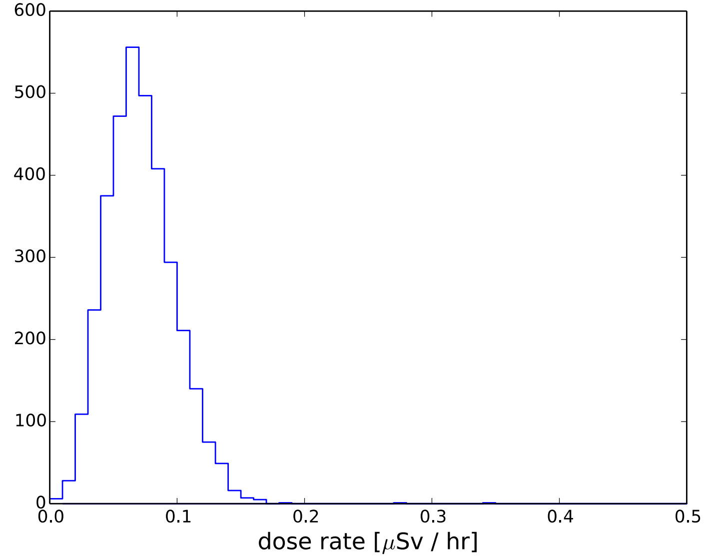
- Operational test in realistic conditions ongoing since April 3rd
- A regular waste container equipped with 8 sensors
- Each sensor housed in a waterproof box and protected by a light metal shield
- Over 5 months the stability of the response of the sensors has been tested against:
  - ✓ Temperature variations (from 5 ^{o}C to over 40 ^{o}C inside the container);
  - ✓ Rain and high humidity;
  - ✓ Shaking and mechanical shock during normal use of the the waste container (filling, emptying, etc.)

Test in operational conditions

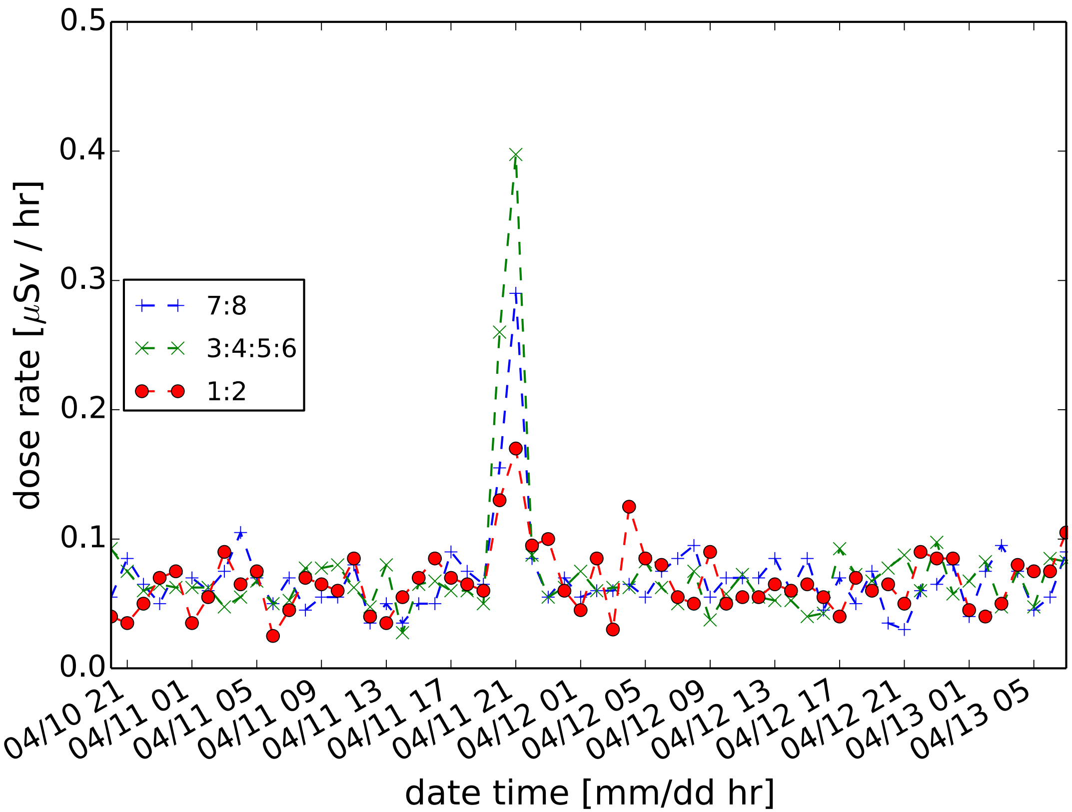




Data recorded every hour on the onboard memory of the D-shuttle. The mean value of the dose rate is 0.09 µSv/hr with almost no reading above 0.2 µSv/hr.



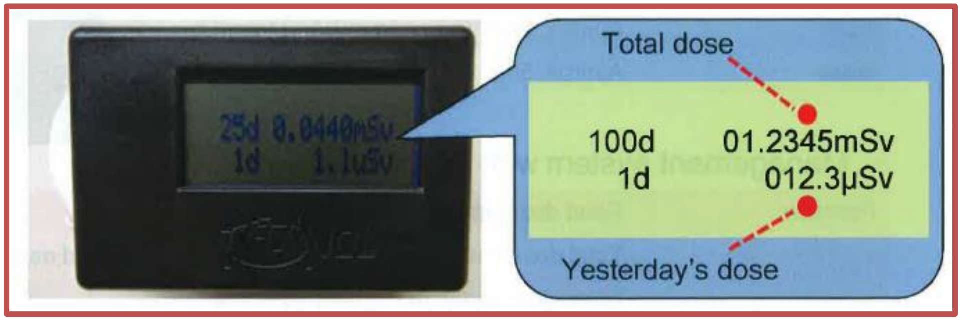
Test in operational conditions



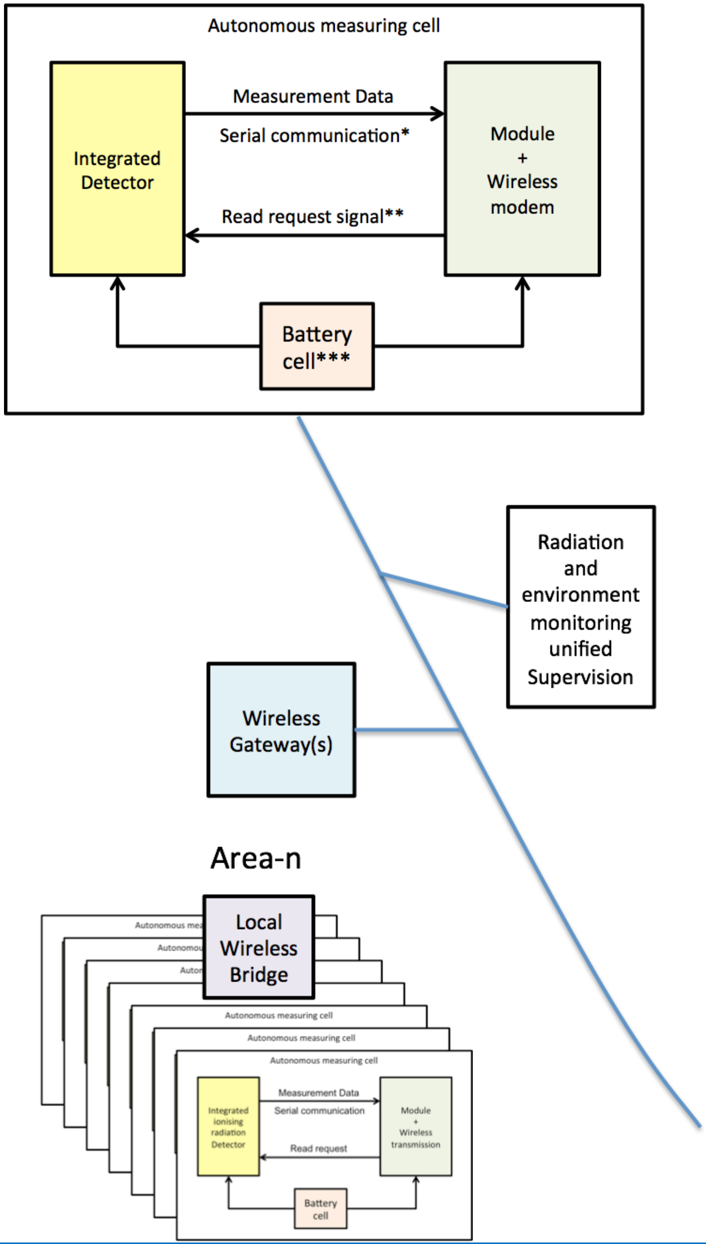
- The spike in dose rate recorded on 11th April between 8 and 9 PM is due to an industrial radiography.
- The sensors in the middle are the more exposed, while the sensors at the bottom see a smaller increase in dose rate.

From manual reading to remote data transfer

- The D-shuttle has short range RF and optical data transfer, triggered by an external magnetic field (reed sensor). Inconvenient for the present application

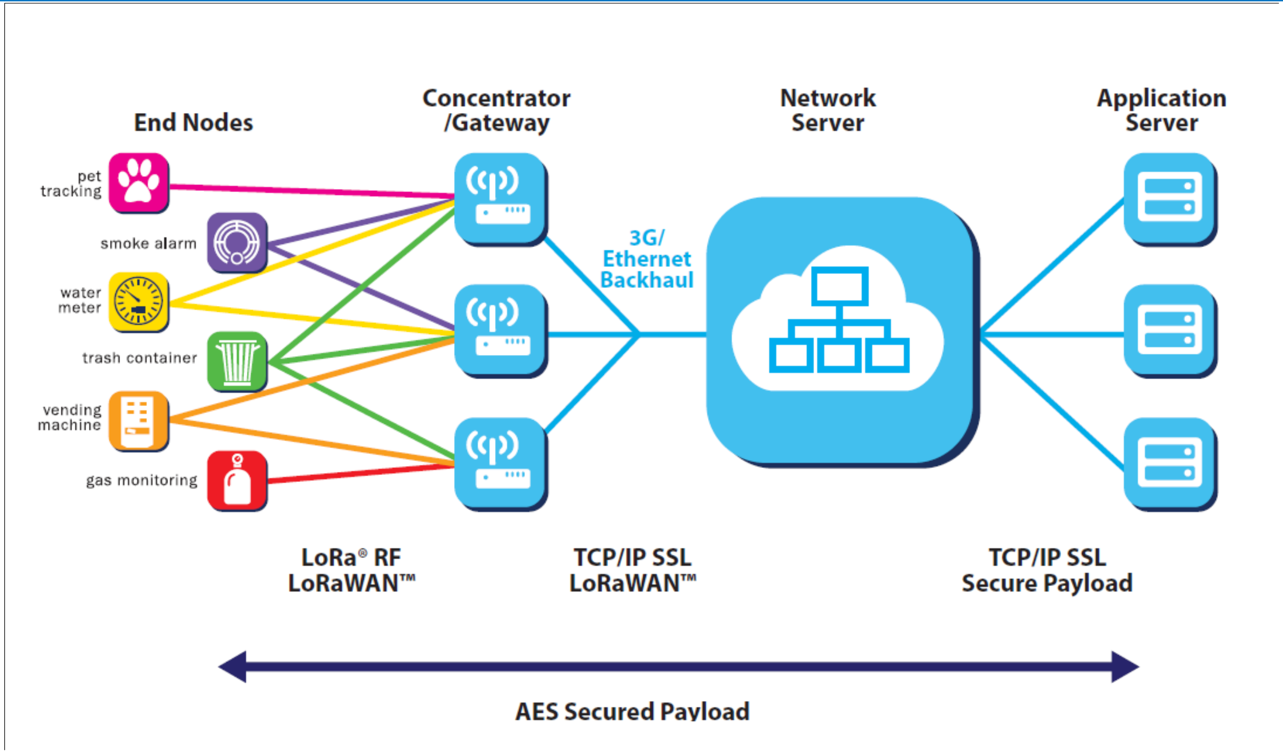


From manual reading to remote data transfer



- The D-shuttle has short range RF and optical data transfer, triggered by an external magnetic field (reed sensor). Inconvenient for the present application
- Through a micro-controller (Arduino for now) we can now:
  - trigger data transfer
  - get the data packets sent through the optical link
  - decode the data packets and extract useful information.
- New developments in ultra low power, long range RF (LPWAN) : LoRa, Sigfox. Tried Sigfox first with good results, now working on LoRa

LoRaWAN



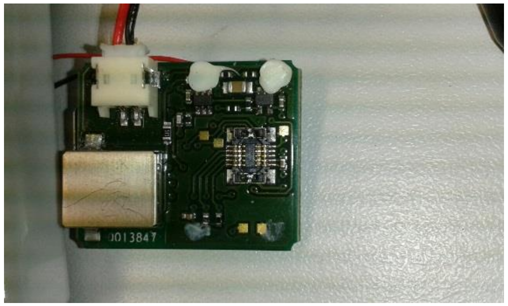
(Internet security protocol)

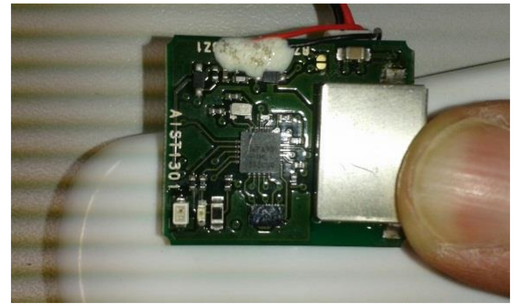
Communication protocol:

- Long Range Wide Area Network
- IoT applications
- AES secured network
- 15 km gateway range
- Low bit rate -> Low consumption
- Frequency band 868 MHz (EU), (920-925 MHz Japan)

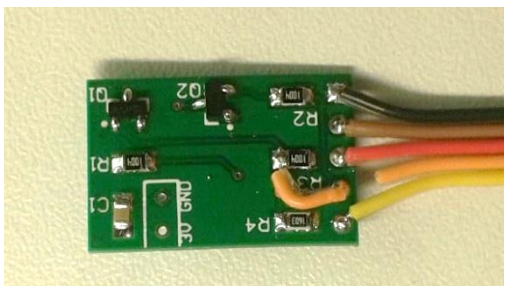
D-shuttle modifications

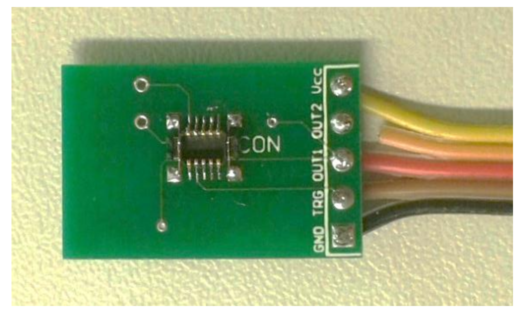
Some minor changes have been applied to the D-shuttle replacing the original "mezzanine" communication board (for RF and optical communication with the reader) with a new one for the extraction of the data



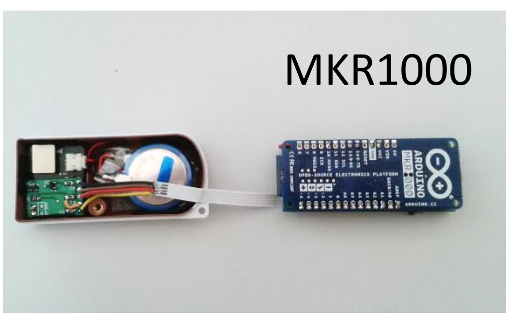


Motherboard



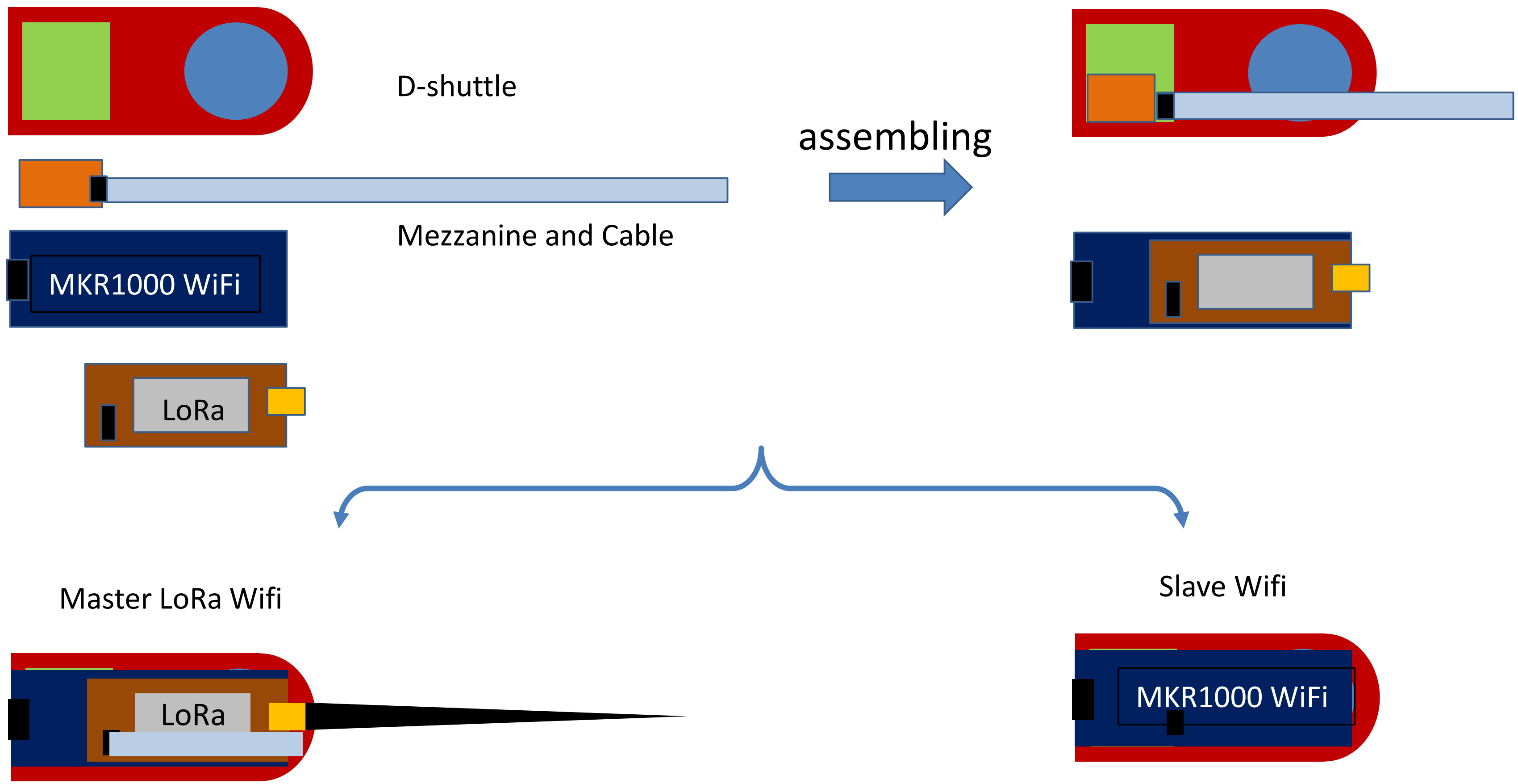


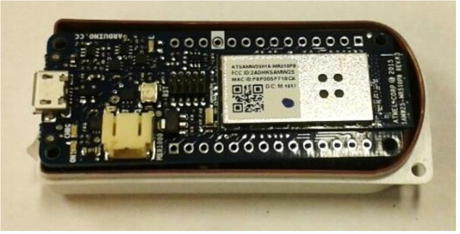
New mezzanine



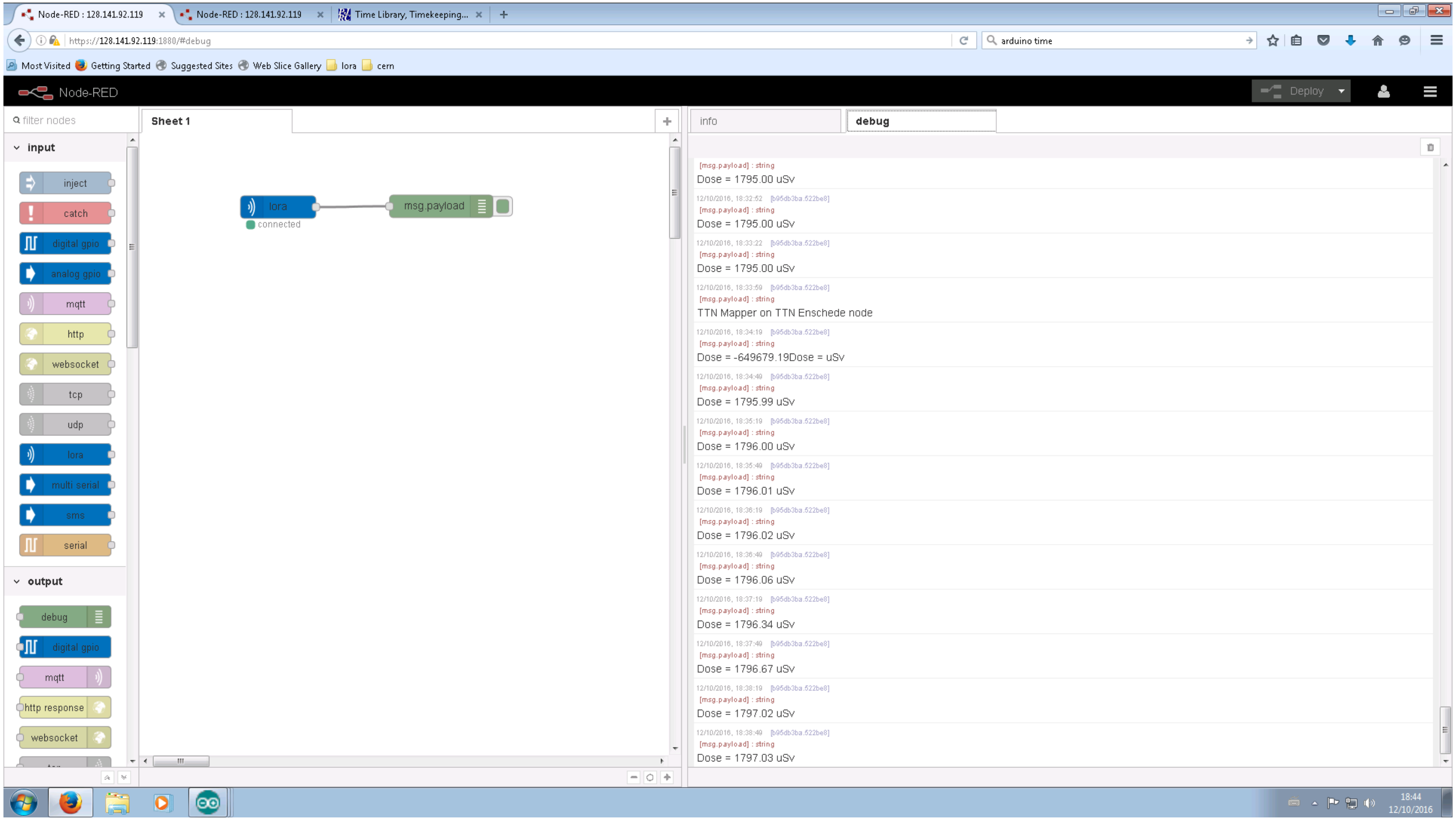
The dosimeter and the CPU are decoupled

D-shuttle assemblies for wireless communication





Data transmission



Remote Pc

NOISE generated by CERN *mezzanine* (now solved)

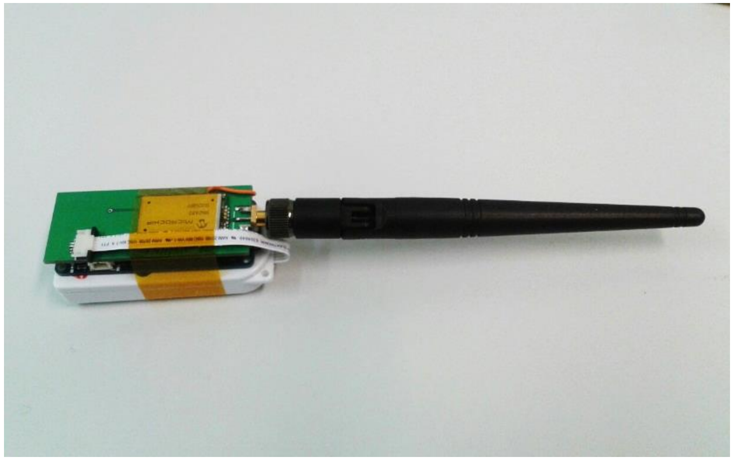
NO GAMMA SOURCE

GAMMA SOURCE

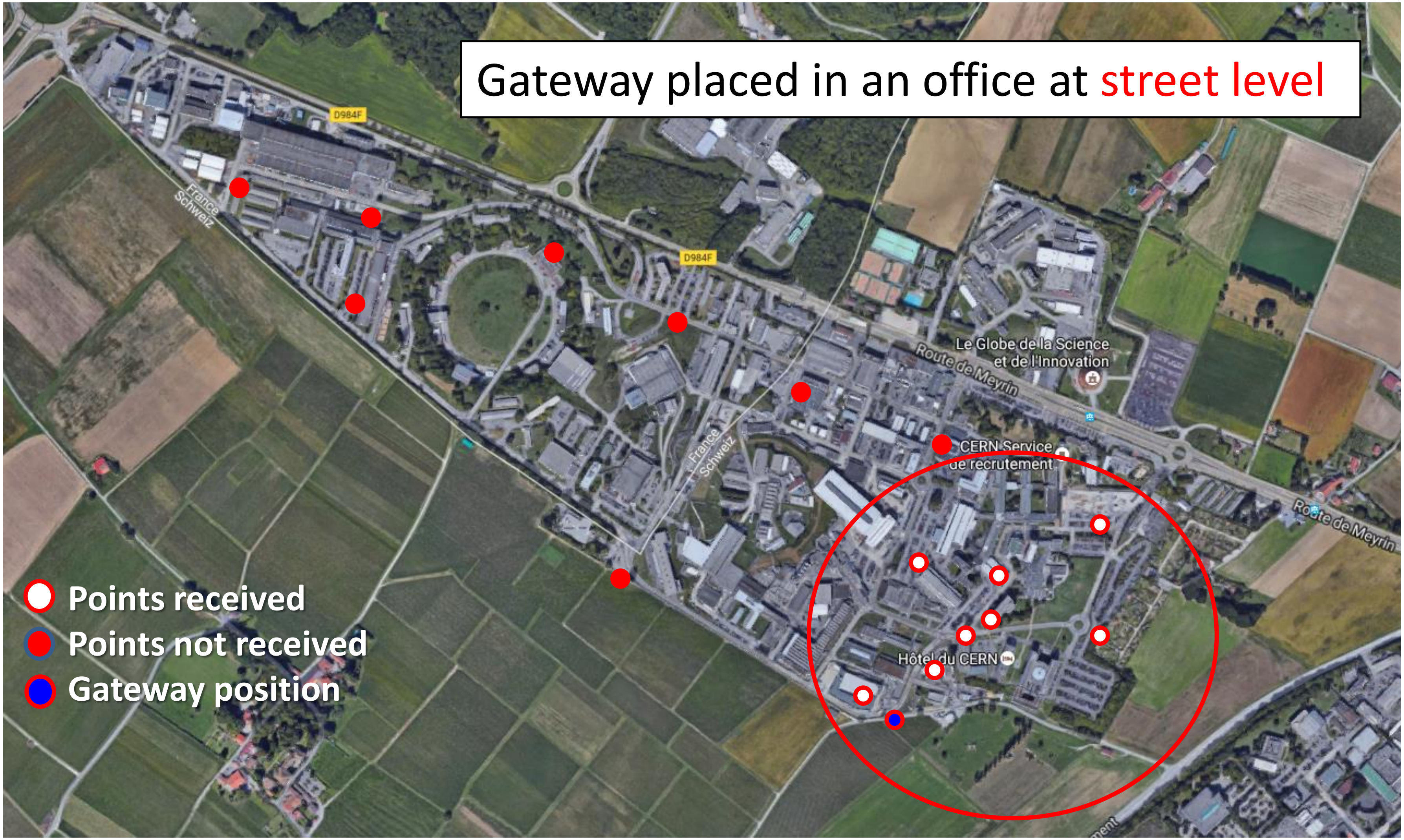
Decoded and transmitted data from D-shuttle to remote PC through the LoRa communication protocol

Dose recorded every 30 seconds

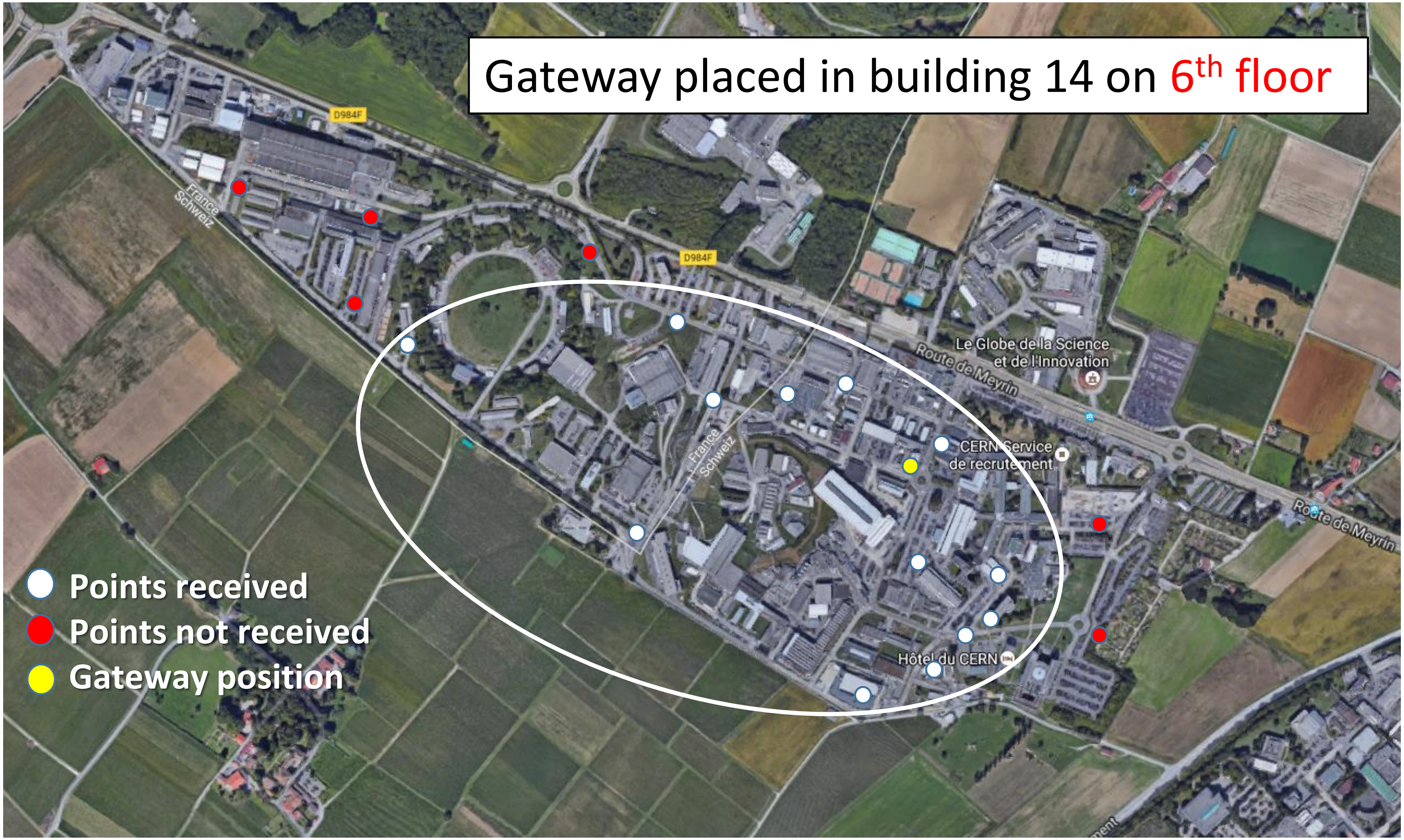
For the W-MON project the data must be collected over a very wide area



A LoRa test system has been set-up to determine the measuring range at CERN


Gateway placed in an office at street level
Points received
Points not received
Gateway position
D984F
D984F
France Schweiz
France Schweiz
Le Globe de la Science et de l'Innovation
Route de Meyrin
Route de Meyrin
CERN Service de recrutement
Hôtel du CERN

Lora range test @ CERN



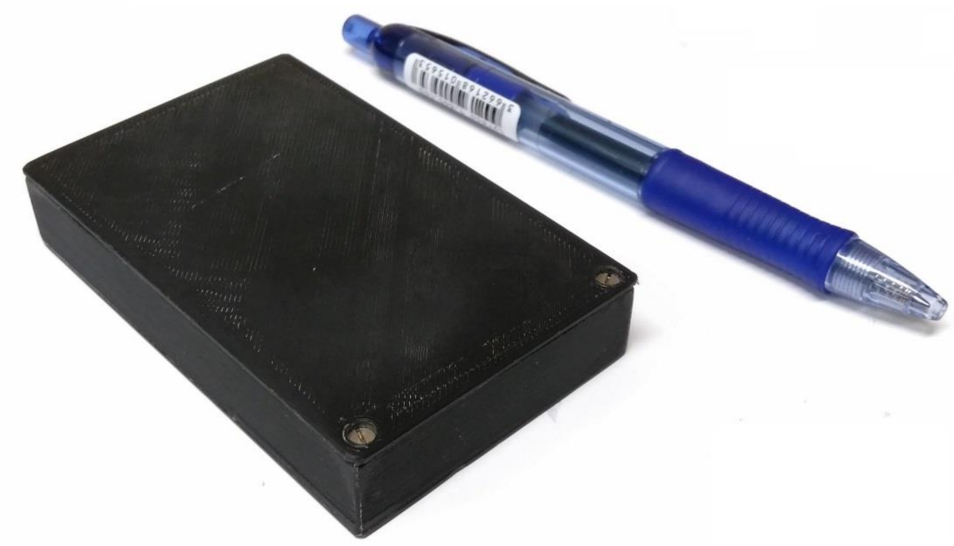
Further locations (the water tower) are being investigated to reach the entire CERN territory

Possible W-MON architecture

Procedure :

1) The master waits for the data from the dosimeters through WiFi
2) Sends all data through LoRa
3) Synchronizes the slaves and everybody sleeps for one hour

The present W-MON prototype

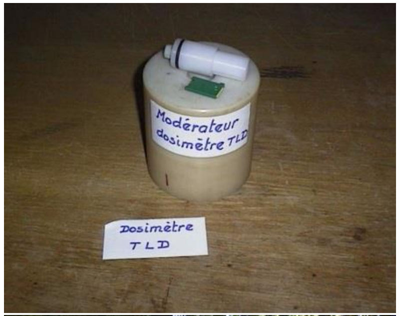


The next steps of W-MON

1. LoRa range test extended over the entire CERN sites
2. Compatibility tests of LoRa with existing CERN IT infrastructure
3. Set-up data transfer from D-shuttle to REMUS
4. Optimize/reduce power consumption !
5. Pilot phase with a few containers equipped with 8 to 10 D-shuttles with automating data log via LoRa and integration with REMUS
6. Full scale project

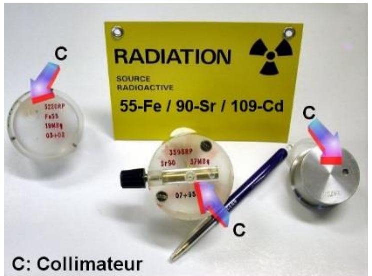
There might be an interest by **Chiyoda** and other companies in CERN developments

- **Distributed network of sensors**: environmental monitoring of large areas, providing the environmental gamma dose in real time with high granularity



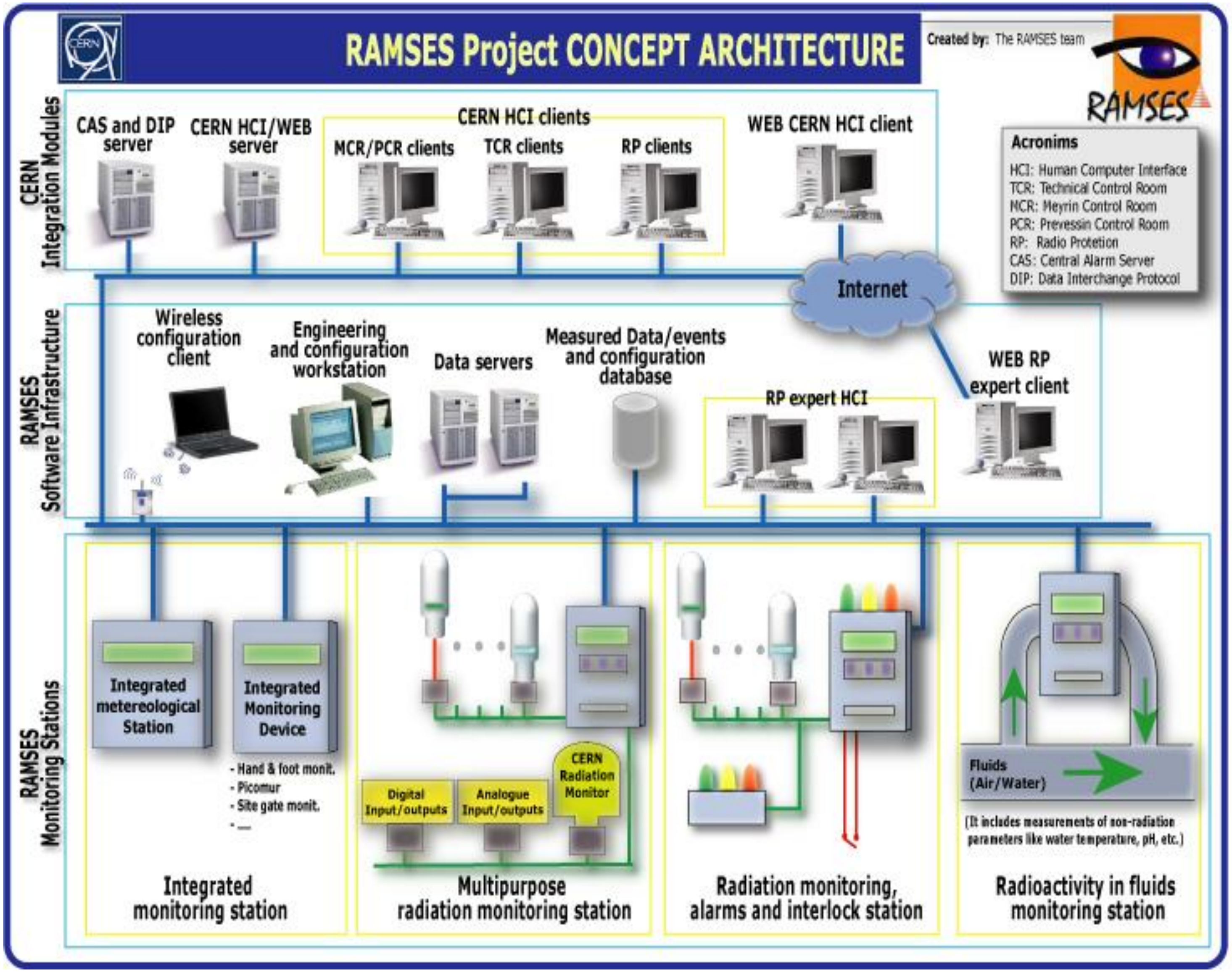
- **Personal dosimetry**: D-shuttle/DIS/DMC comparison

- **Automatic tracking of radioactive sources**



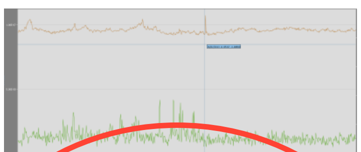
- **Tracking of transport of radioactive materials**

CERN radiation monitoring system (RAMSES)



CERN environmental monitoring program

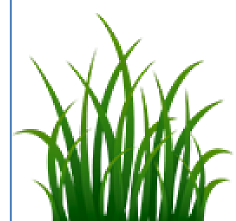
Stray radiation



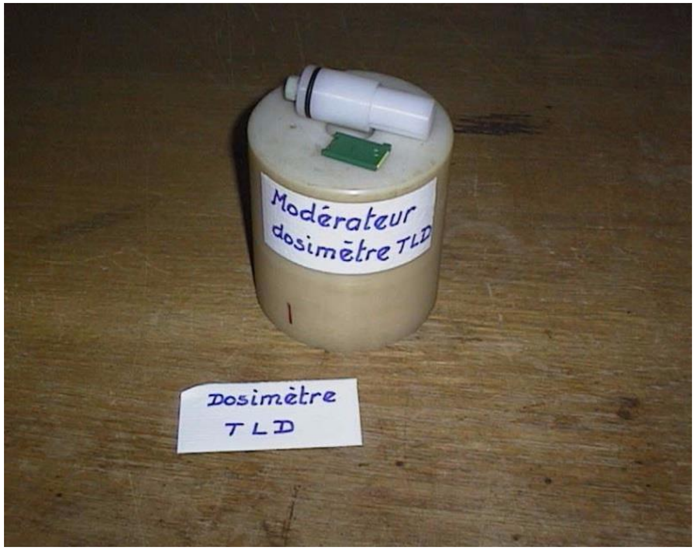
Air

Water

Other environmental samples

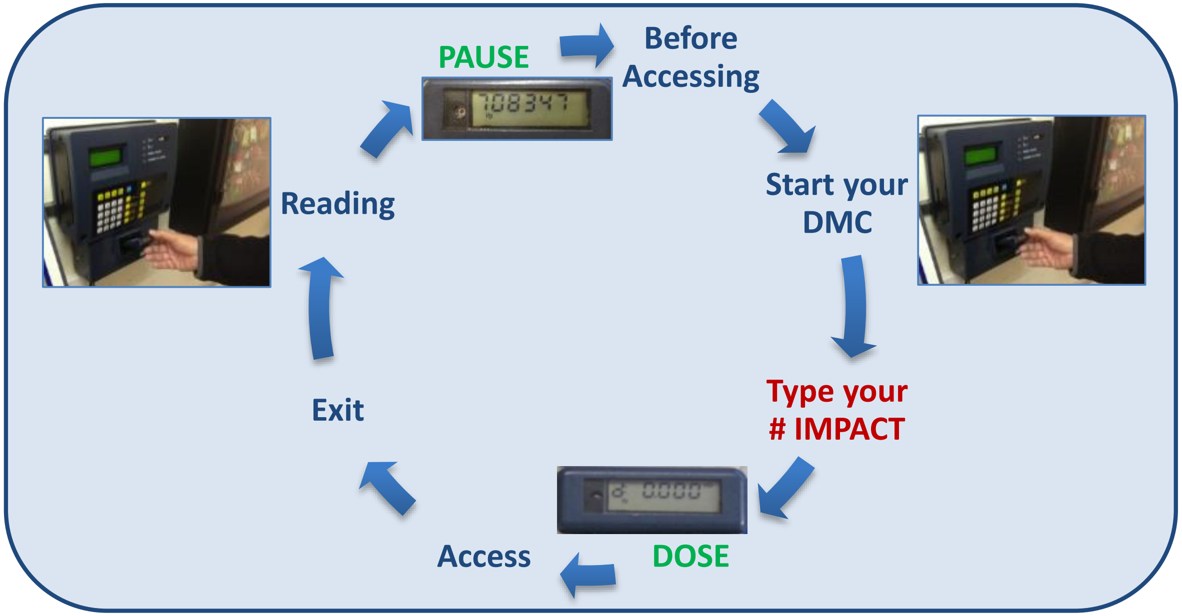


Thermoluminescence dosimeters (TLD) inside a polyethylene moderators are used to monitor neutron and gamma doses in the experimental areas and in the environment.



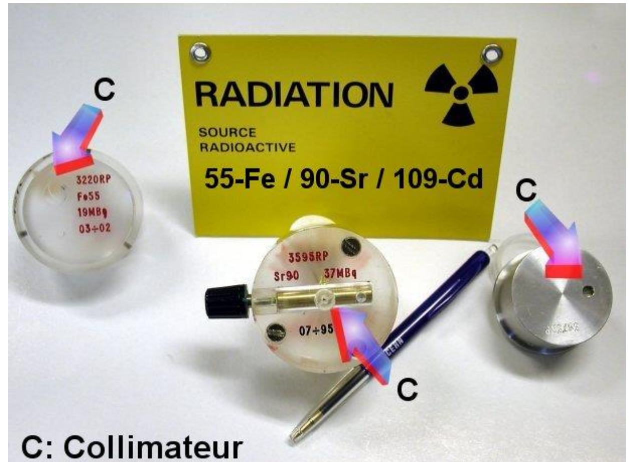
TLDs are passive devices used CERN-wide to integrate radiation doses over a period of several months.

DIS personal dosimeter: "Legal dose”



The DMC gives a signal in the presence of ionising radiation, e.g. a warning in case one passes by undeclared radioactive material (or the other way around)


7164


RADIATION
SOURCE
RADIOACTIVE
55-Fe / 90-Sr / 109-Cd
C
C
C
C
3220RP
Fe55
19MBq
03÷02
3595RP
Sr90
37MBq
07÷95
C: Collimateur


CERN
GE 609 267
268

- **Homeland Security**
- Remote environmental monitoring in the **Fukushima area**
- **Medical applications**: on-line dosimetry for interventional radiology


Interventional Radiology Operating Room,
2425 Geary Boulevard San Francisco, CA

- **The future?** Direct **integration** in smartphones and other consumer electronics?

Networks of radiation sensors for

- Environmental monitoring
  ➞ Radiation monitoring of waste containers
- Radon monitoring

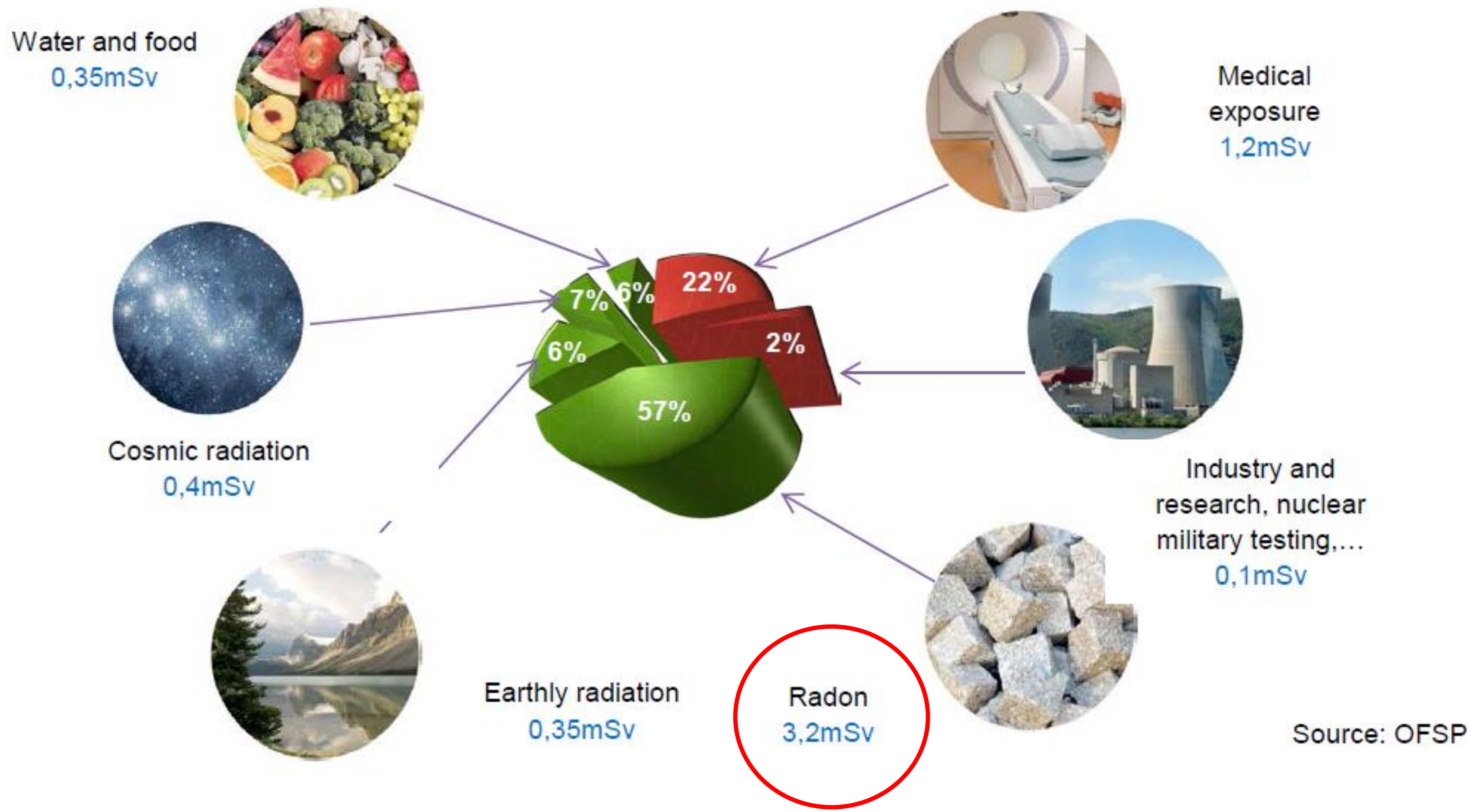
- The radon issue
- Dose to the lung
- The RaDoM concept
- The Network of sensors

http://www.semtech.com/wireless-rf/internet-of-things/

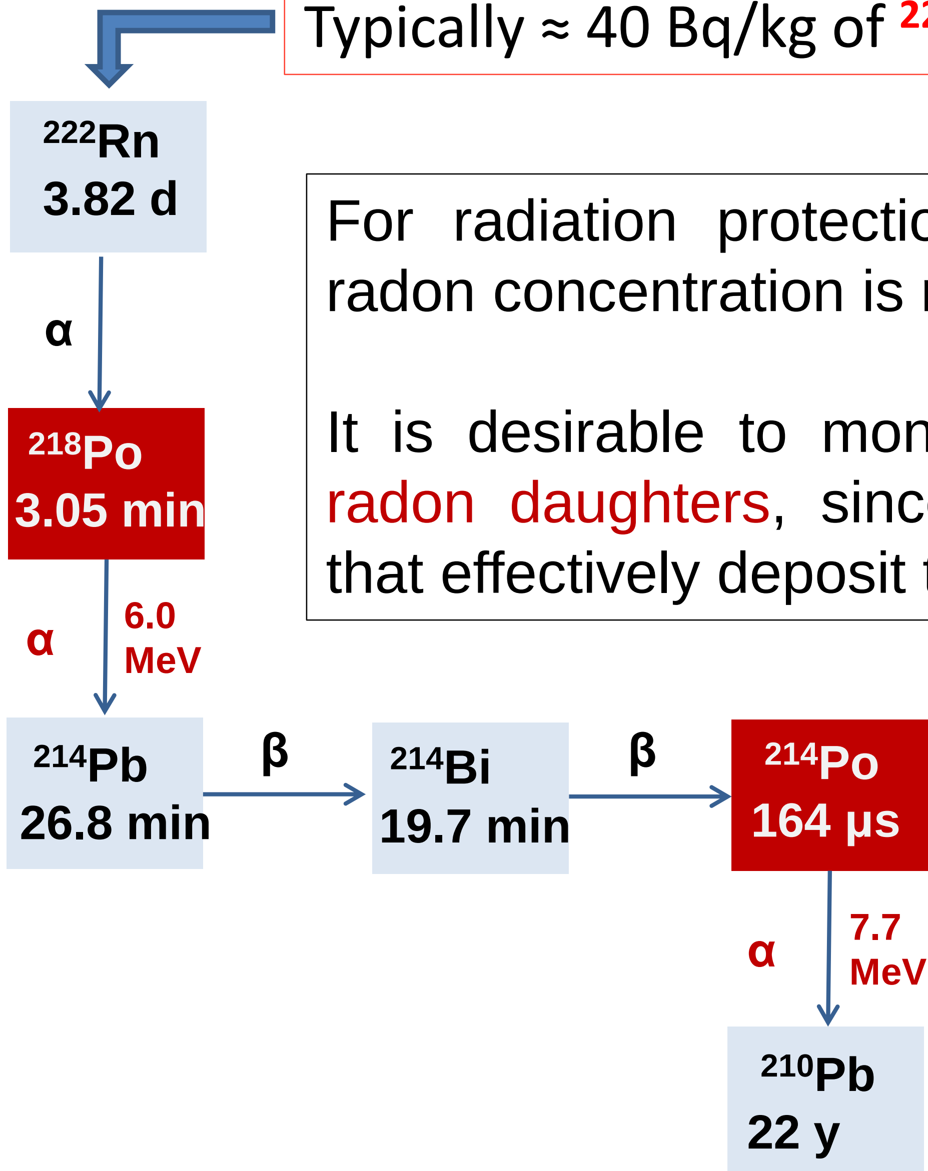
Annual exposure to natural radioactivity in **France** = 2.5 mSv
(3.3 mSv including medical exposures)

Natural radiation exposures

Annual exposure to natural radioactivity in **Switzerland** = 4.4 mSv
(5.6 mSv including medical exposures)



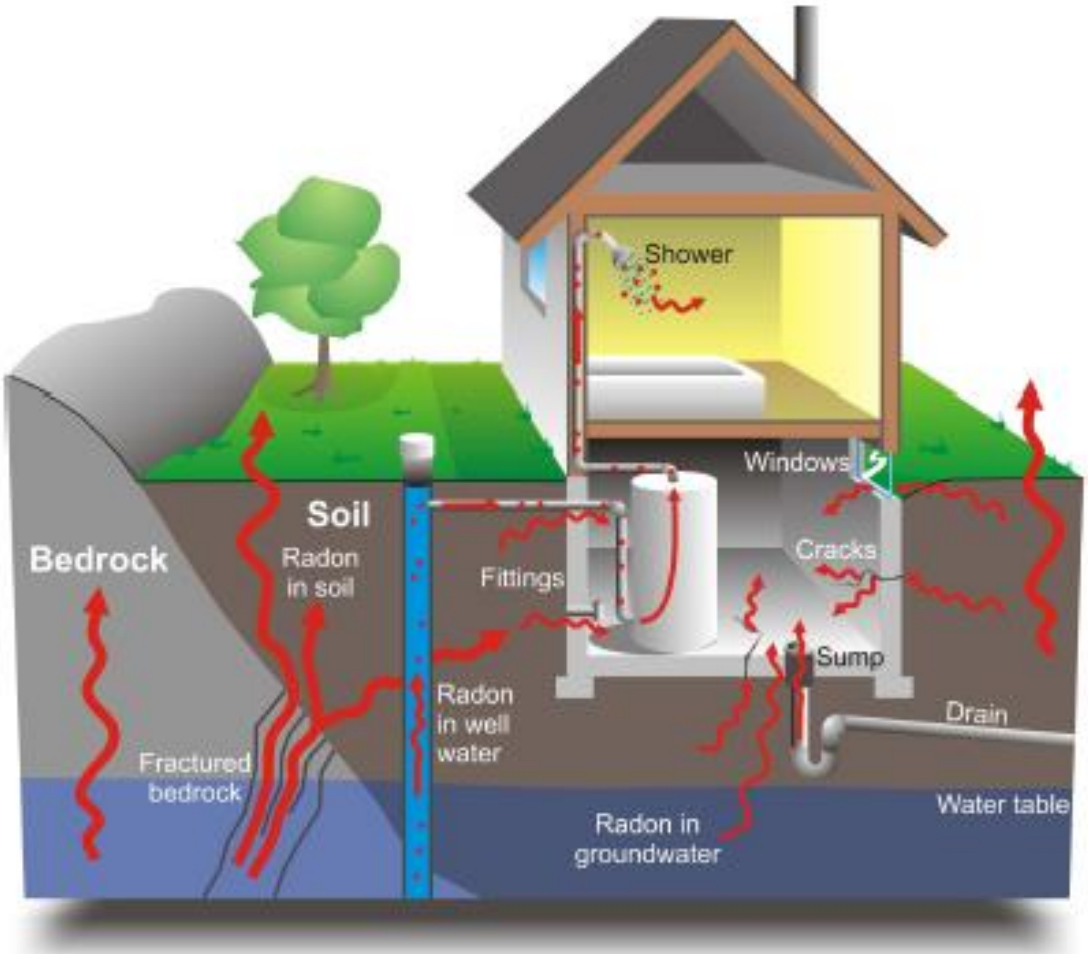
Typically ≈ 40 Bq/kg of ^{226}Ra in rocks and soil



For radiation protection purposes measuring only radon concentration is not sufficient.

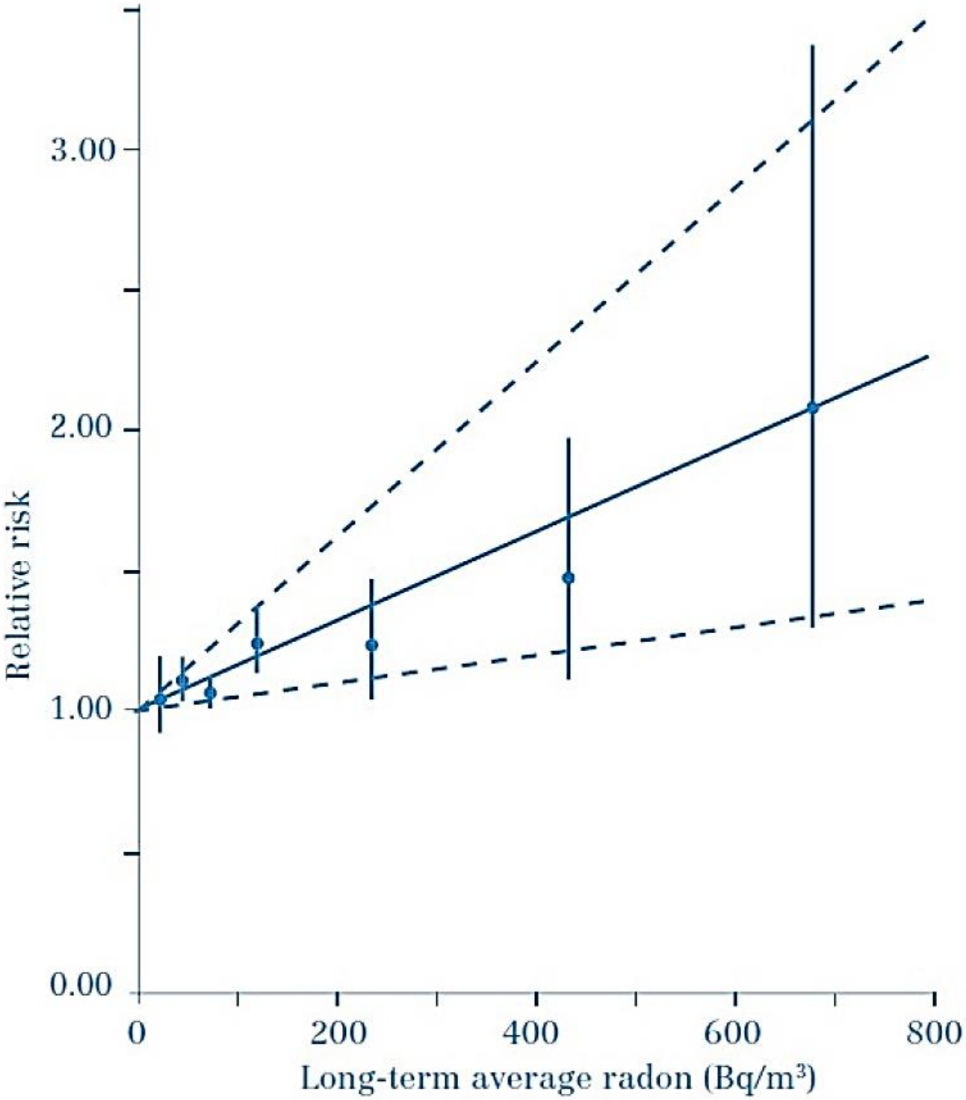
It is desirable to monitor the concentration of the radon daughters, since they are the radionuclides that effectively deposit their energy on the lung tissue

Propagation of radon from soil into buildings



- Radon is emanated from the Uranium rich soil or rocks
- Radon can also be found in water
- Radon escapes easily from the ground into air where it decays into its *progeny*.

Relative risk of lung cancer



Darby, S et al. BMJ 330, 223-227 (2005)

RR = ratio of the probability of a disease occurring in the exposed group versus a non-exposed group

According to WHO:

Intervention level: 100 Bq/mc

100 Bq/mc Effective Dose: 5 mSv/y

Lung cancer risk over 40 years:
0.67 – 1.25 %

Percentage of lung cancer attributable to radon

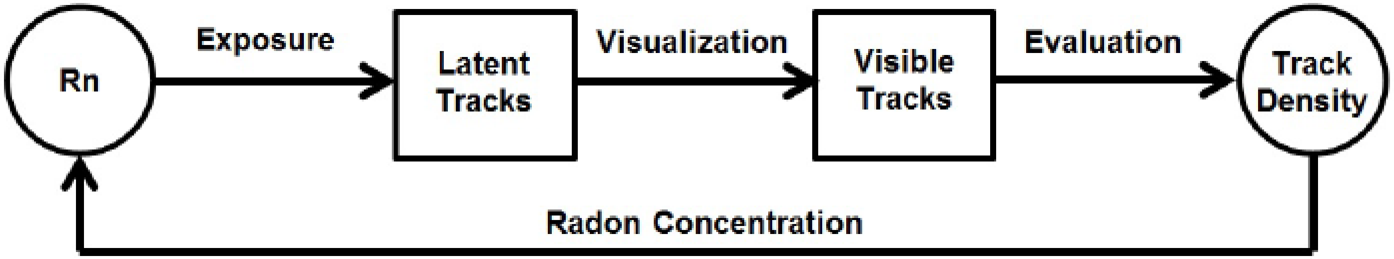
Country	Mean indoor radon [Bq/m^3]	Risk estimate used in calculation	Lung cancer attributed to radon [%]	Estimated no. of deaths due to radon-induced lung cancer each year
Canada [14]	28	BEIR VI	7.8	1400
Germany [15]	49	European pooling study	5	1896
Switzerland [15]	78	European pooling study	8.3	231
United Kingdom [16]	21	European pooling study	3.3	1089
		BEIR VI	6	2005
France [17]	89	European pooling study	5	1234
		BEIR VI	12	2913
United States [18]	46	BEIR VI	10-14	15400 - 21800

Passive radon measurements with track detectors

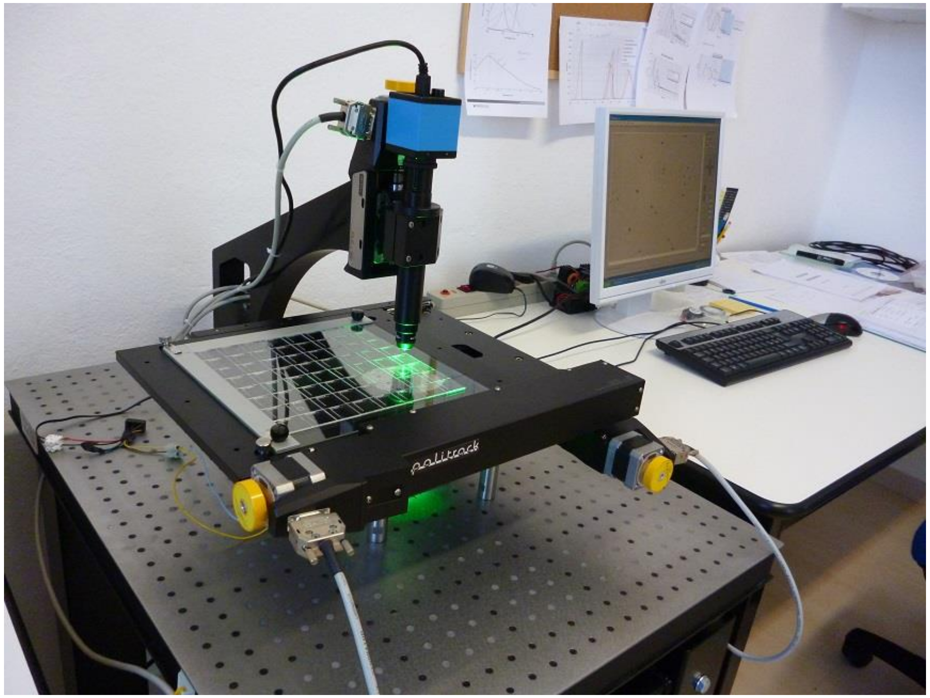
Quantity measured: kBq*h/m^3
Measurement time: a few months (up to 6)

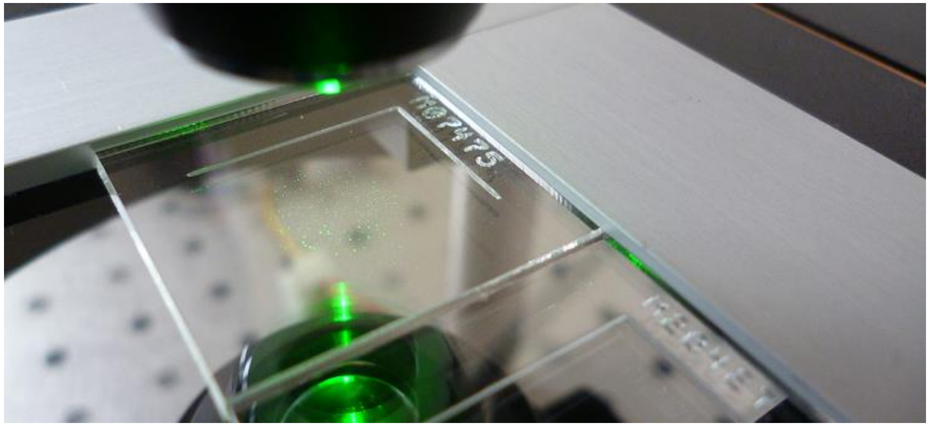
DETECTOR
CR-39
25 x 25 mm^2
15 x 15 mm^2
Thickness 1.5 mm

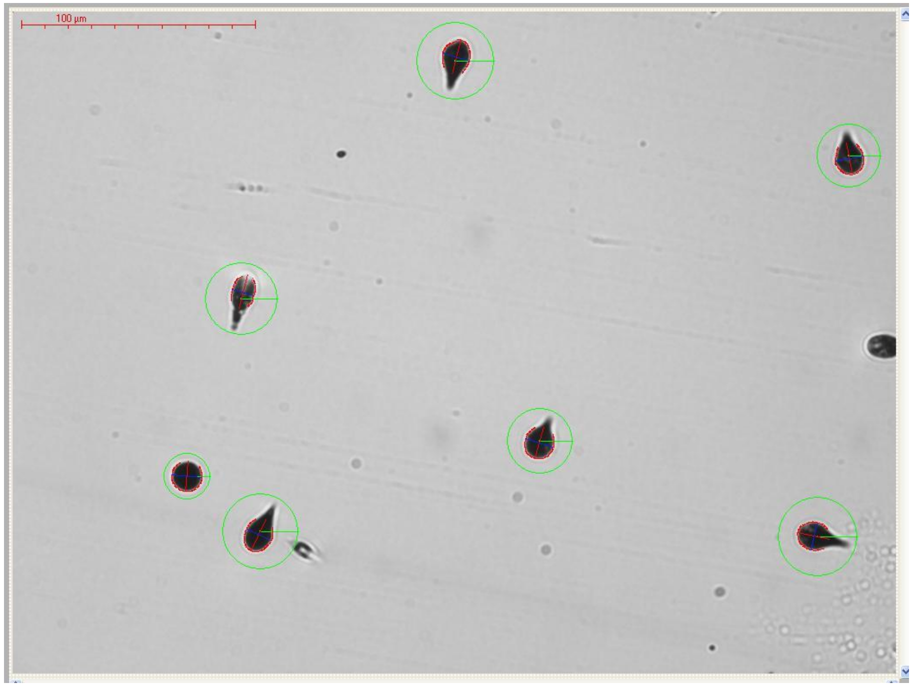
HOLDER
Model HM-10
Diameter 50 mm
Height 20 mm



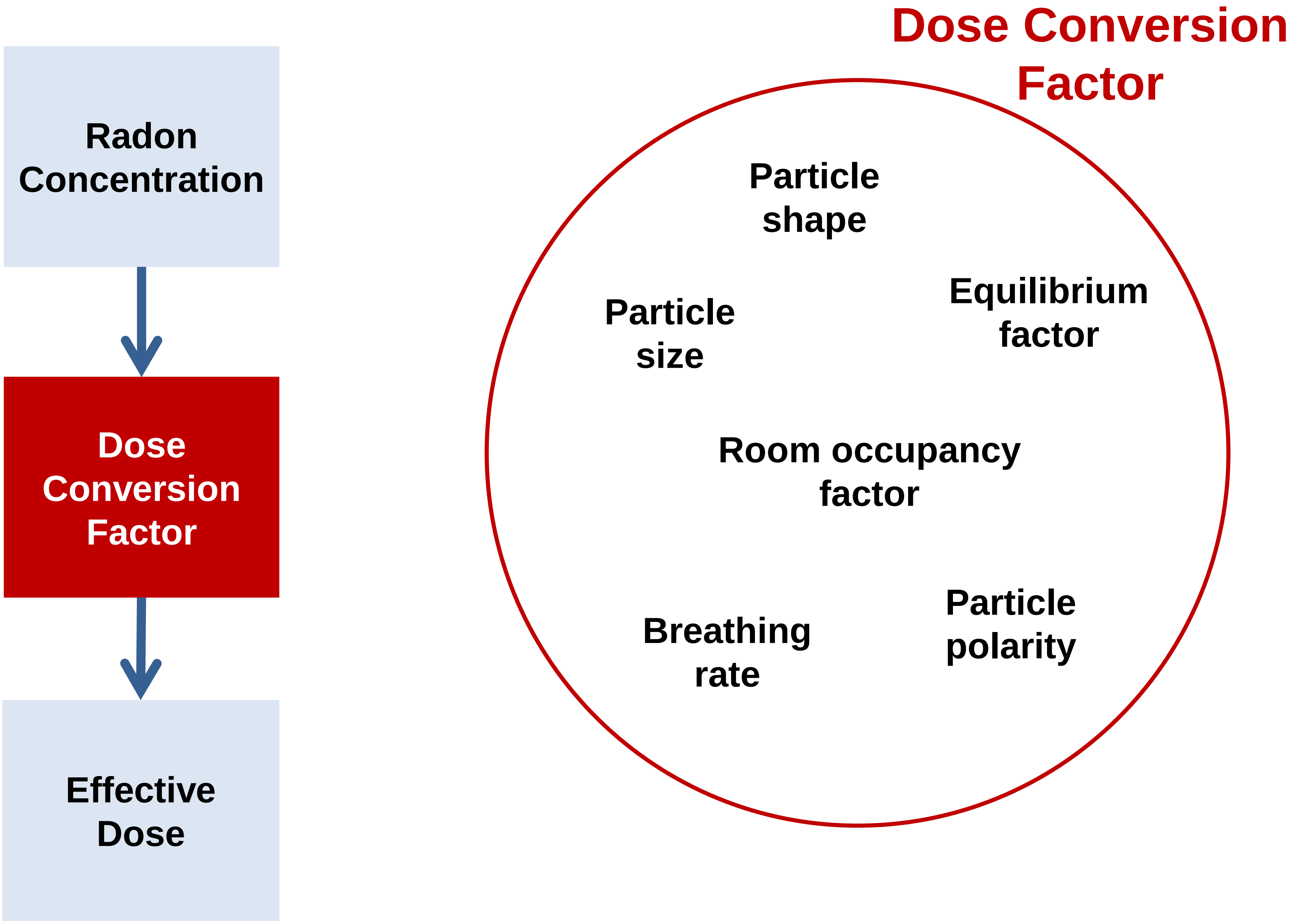
Passive radon measurements with track detectors







Active radon instrumentation


Radon Concentration
Dose Conversion Factor
Effective Dose
Dose Conversion Factor
Particle shape
Particle size
Equilibrium factor
Room occupancy factor
Breathing rate
Particle polarity

The RaDoM Idea

Radon Concentration

Dose Conversion Factor

Effective Dose

Dose Conversion Factor

Particle shape

Particle size

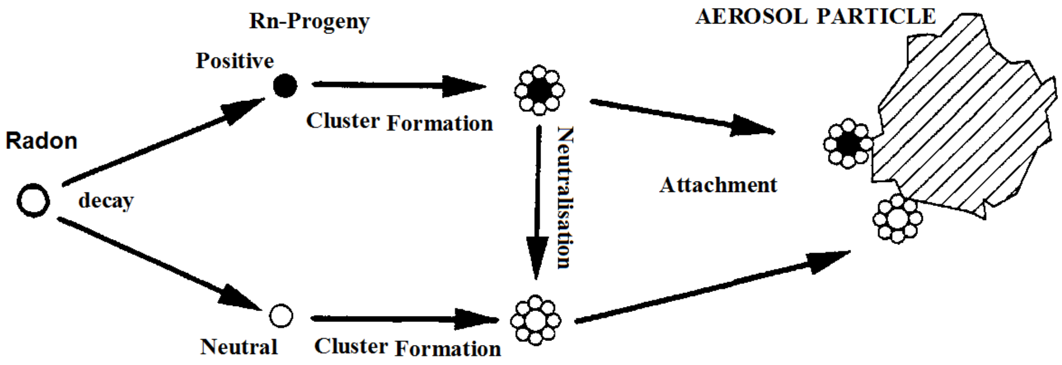
Equilibrium factor

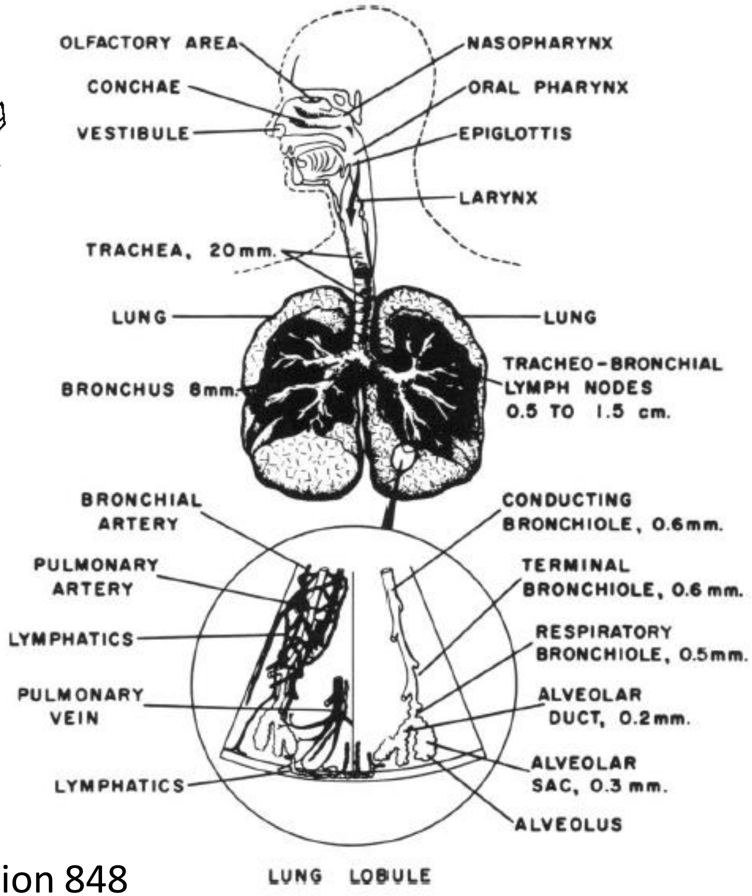
Room occupancy factor

Breathing rate

Particle polarity

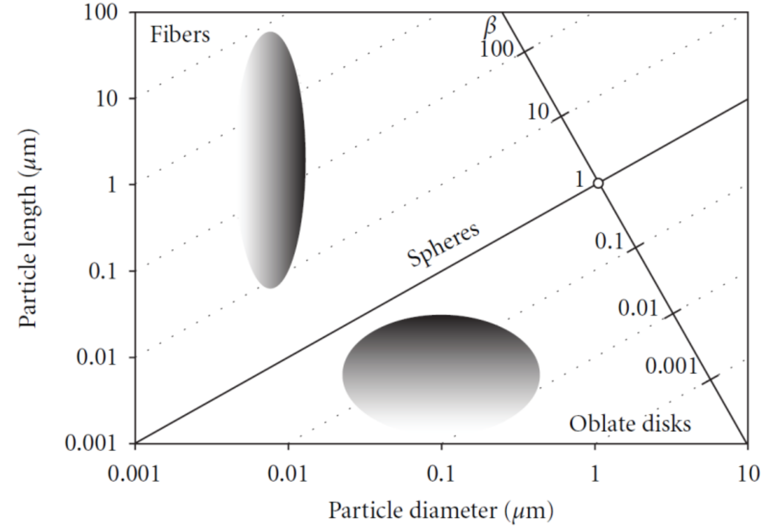
A large fraction of radon decay products (80%-82%) attach to aerosol particles which are suspended in air forming radioactive aerosol.

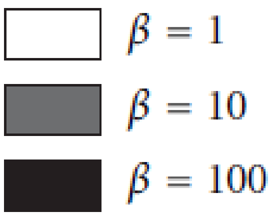




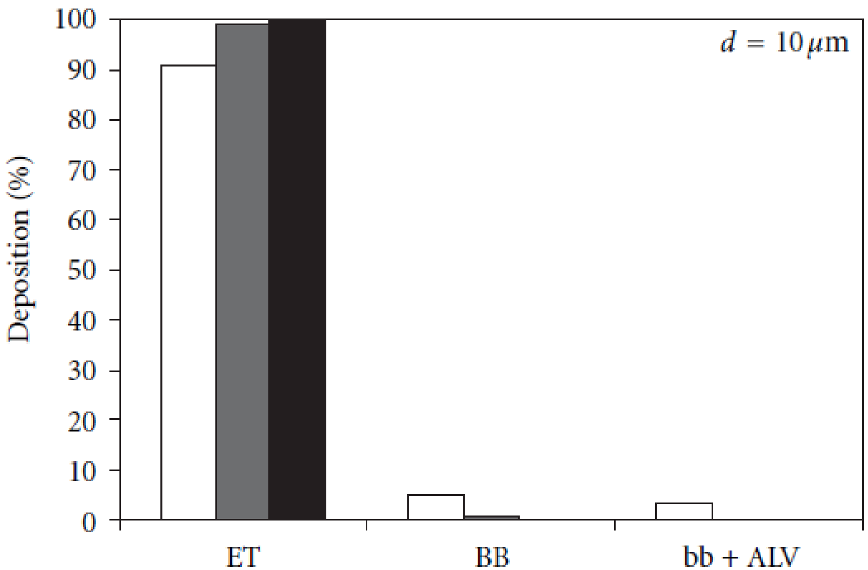
National Academy of Sciences, NAS-NRC Publication 848

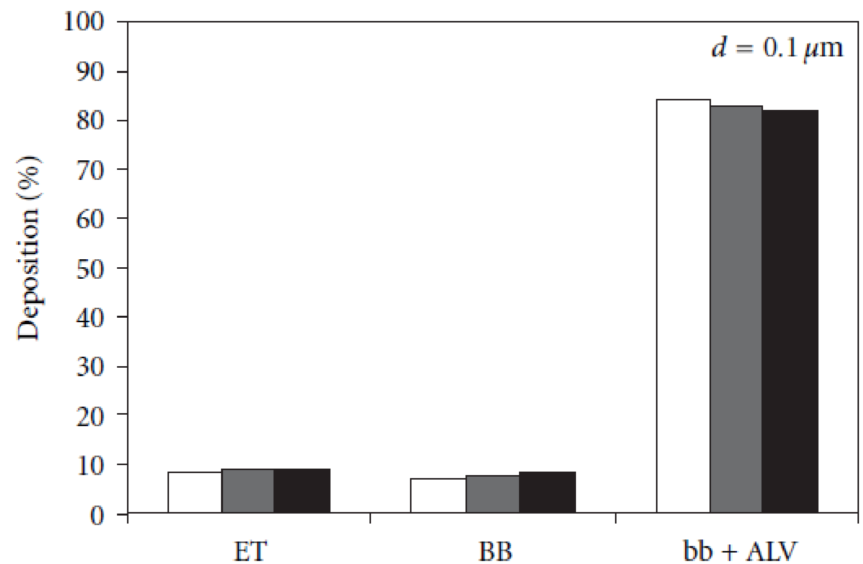
The deposition rate of radioactive particles in the human respiratory track varies a lot due to the different particle sizes and shapes



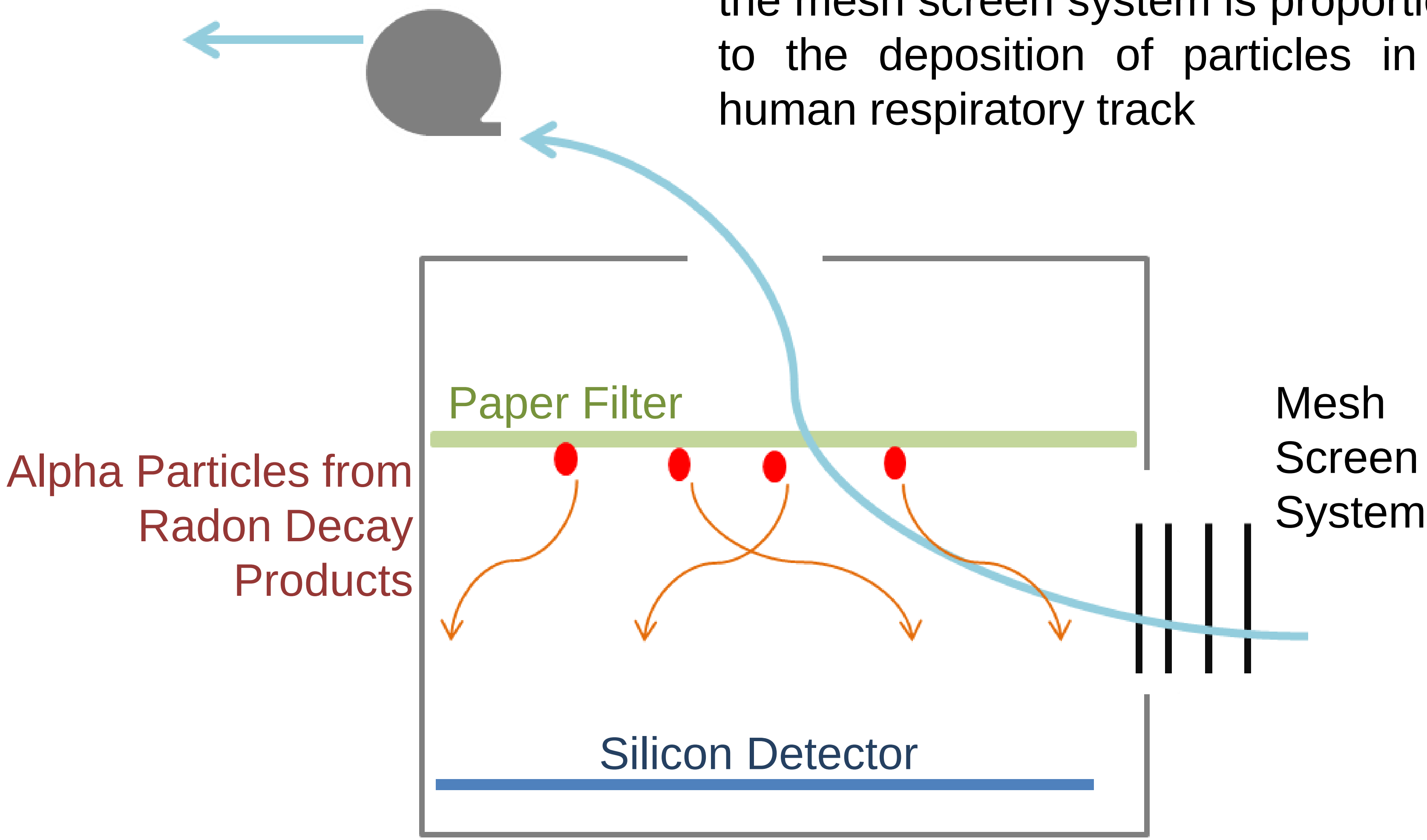


- ET: EXTRATHORACIC
- BB: BRONCHIAL
- bb+ALV: BRONCHIOLAR/ALVEOLAR

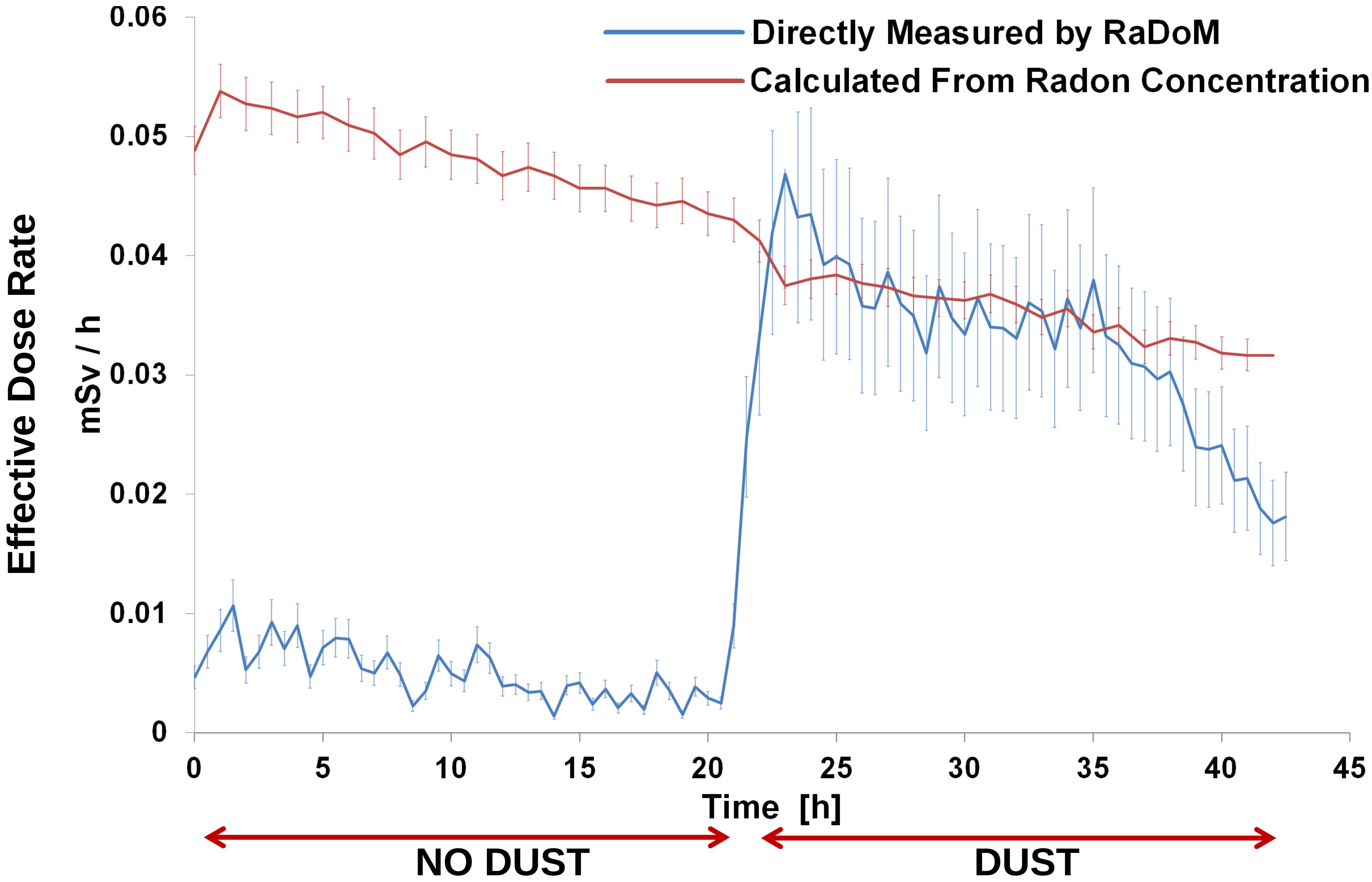




The penetration of particles through the mesh screen system is proportional to the deposition of particles in the human respiratory track

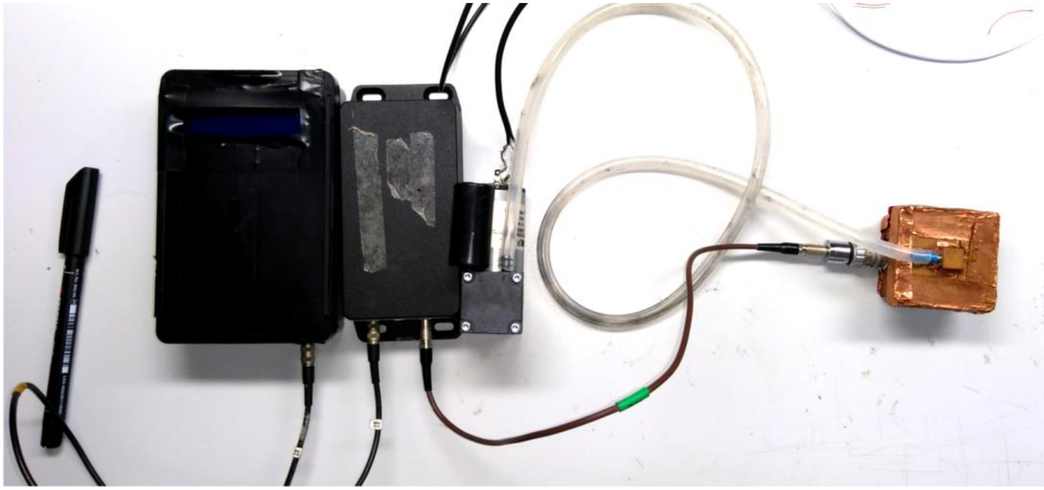


The RaDoM concept

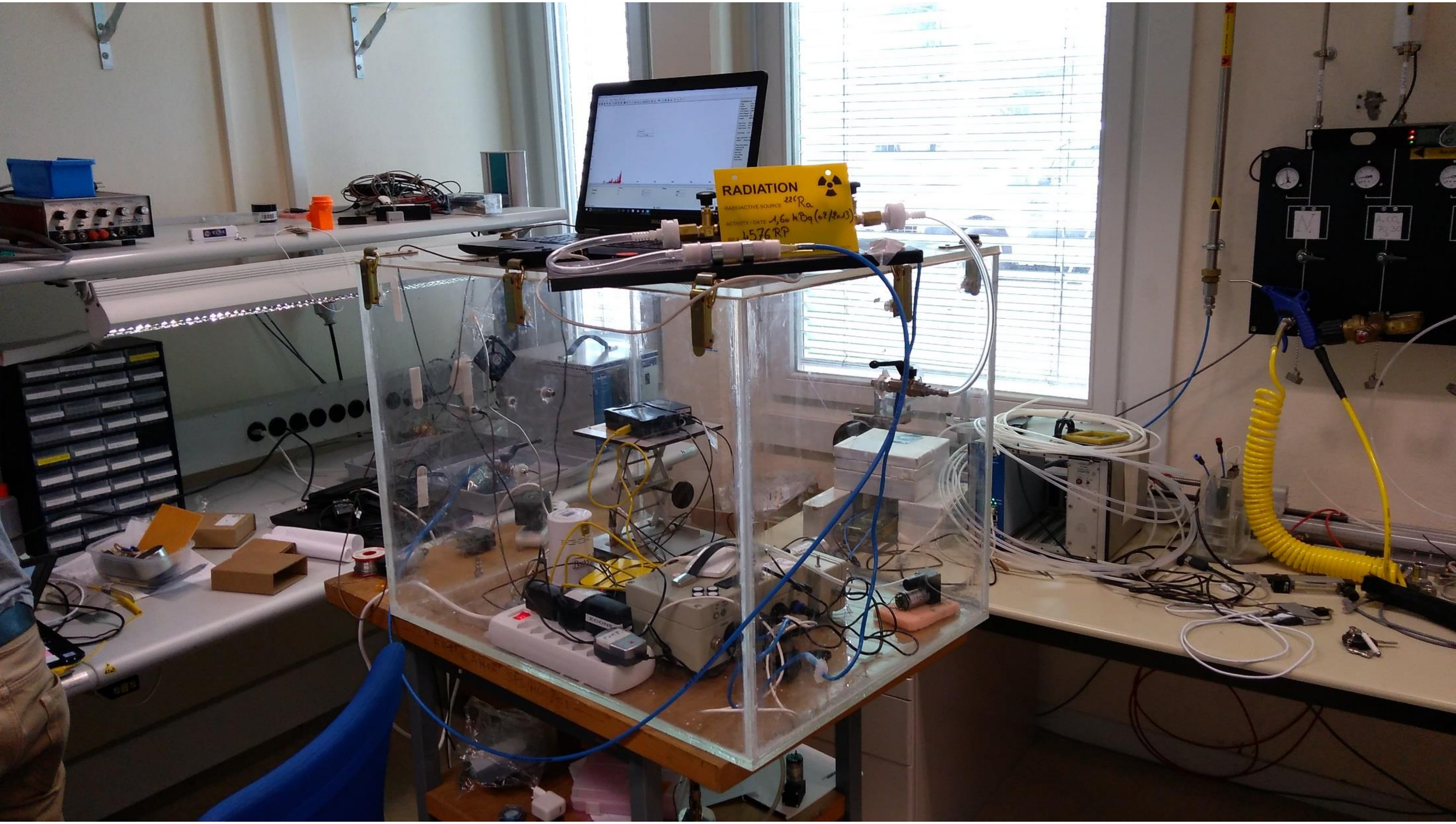



Cremat, Inc.
CR-111
Maintenance-free Sealed Lead-acid Battery
Pb

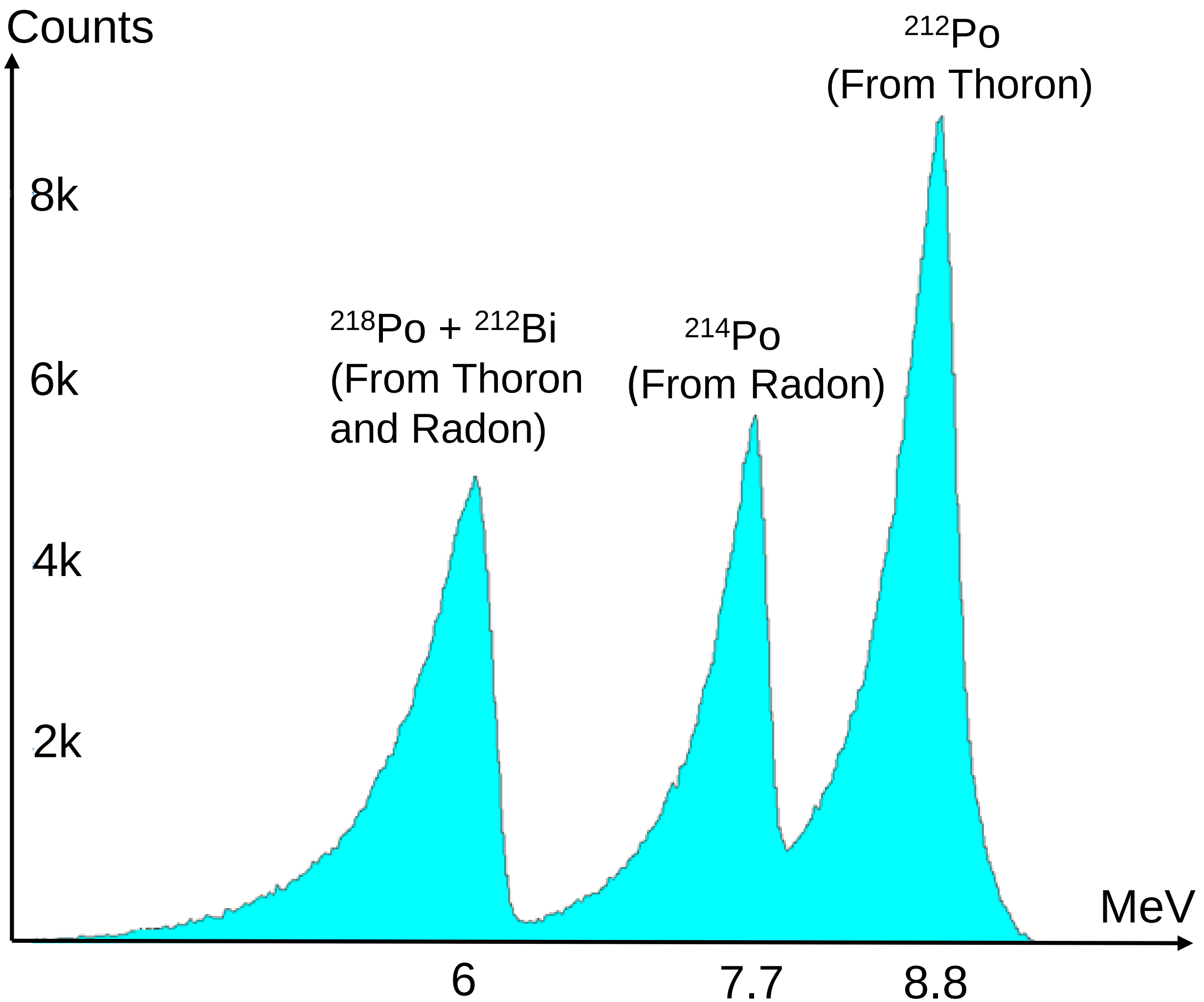
Prototypes



The RaDoM concept

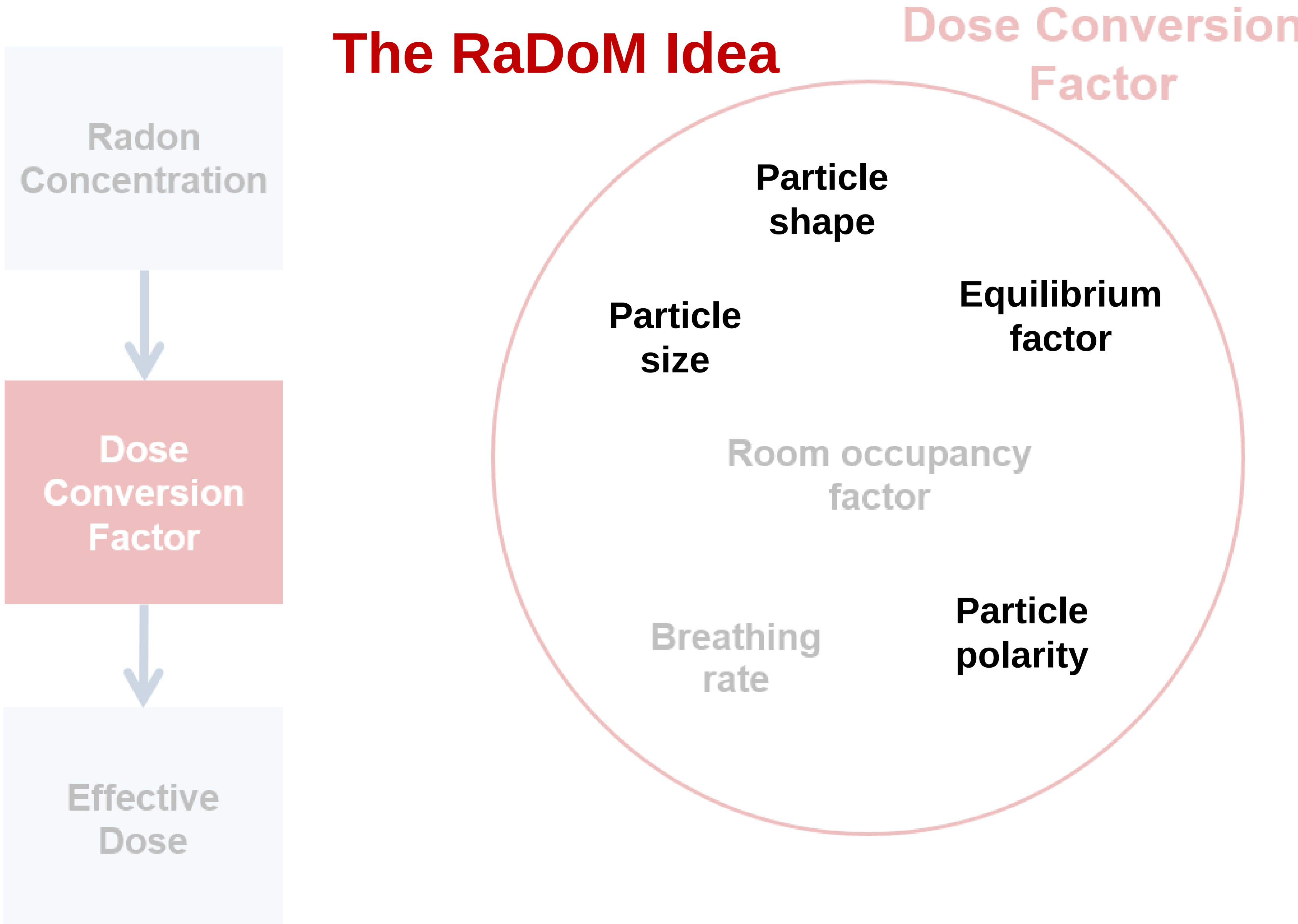


The RaDoM concept



Measuring time: 62 hrs

The RaDoM Idea



Continuous monitoring with a network of sensors

Dose Conversion Factor

Radon Concentration

Dose Conversion Factor

Effective Dose

Particle shape

Particle size

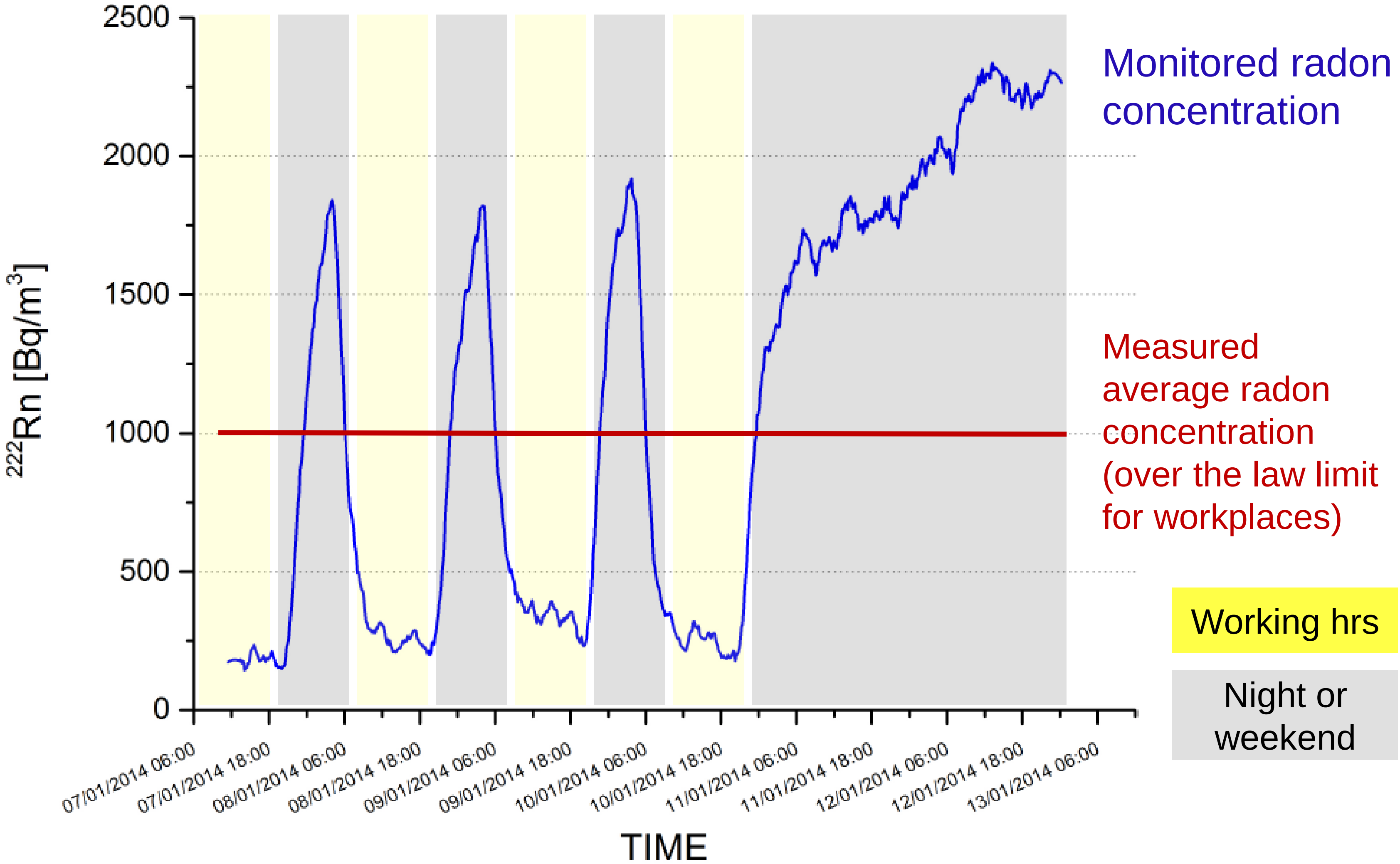
Equilibrium factor

Room occupancy factor = Exposure time

Breathing rate

Particle polarity

Polytechnic of Milan, Italy

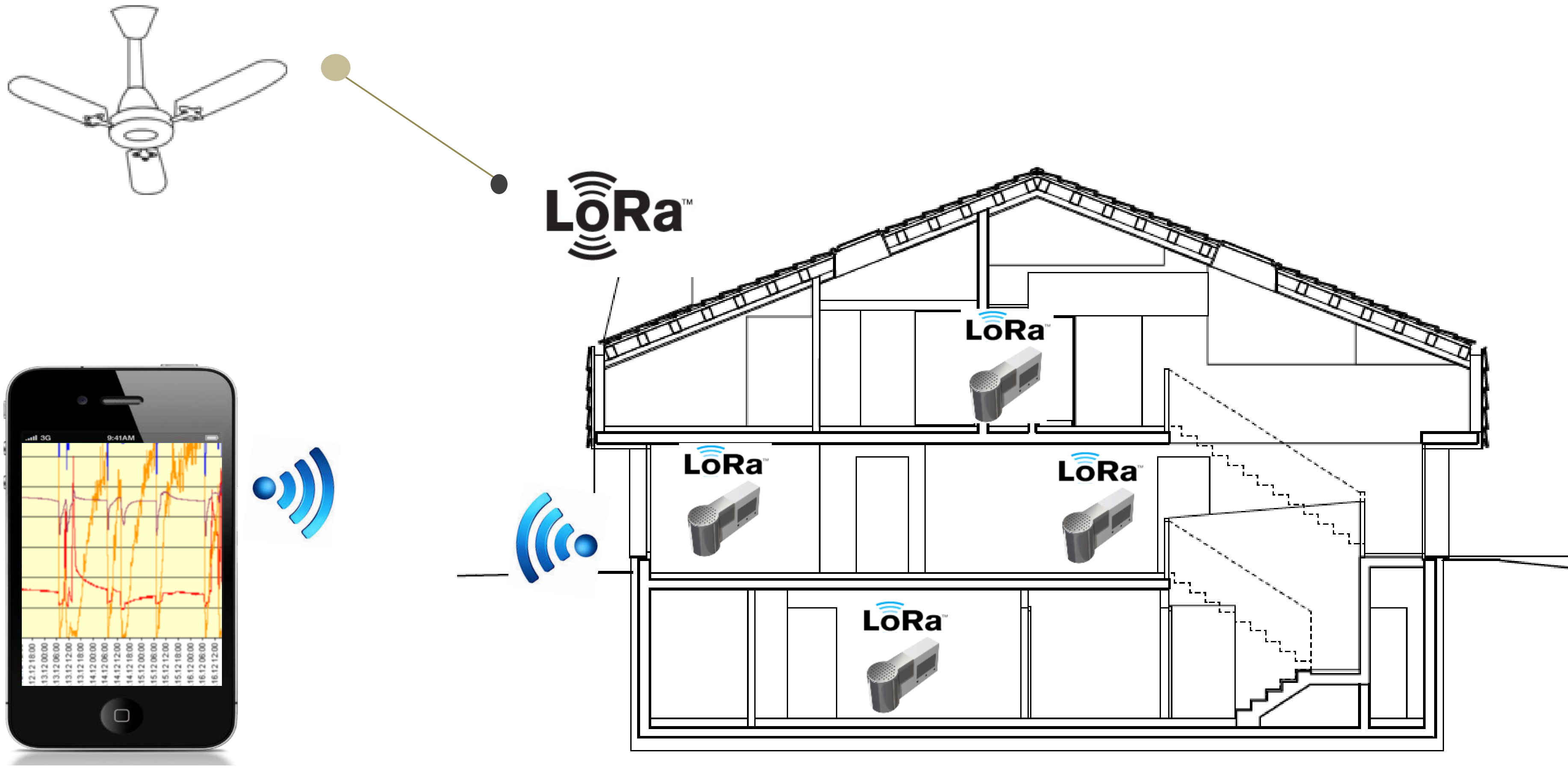


People are safe if they work here. They are not if they live (sleep) here

The network of sensors

The radon concentration is not the same everywhere in a building.

Each room should be monitored for a better estimation of the risk.



THANK YOU FOR YOUR ATTENTION

http://www.semtech.com/wireless-rf/internet-of-things/