BEOBAL FP6 Seminar

Radiological environmental protection at CERN

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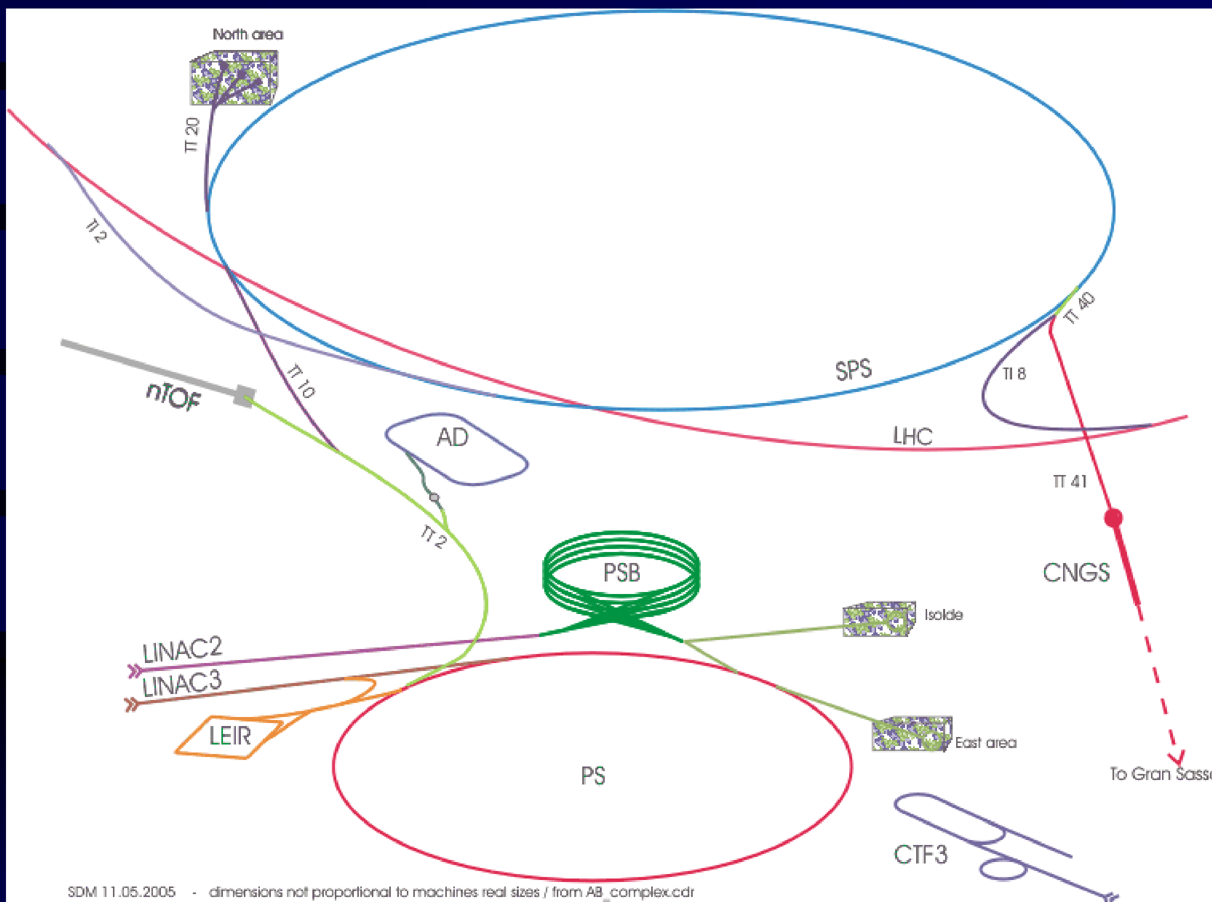
CERN, Safety Commission

Introduction

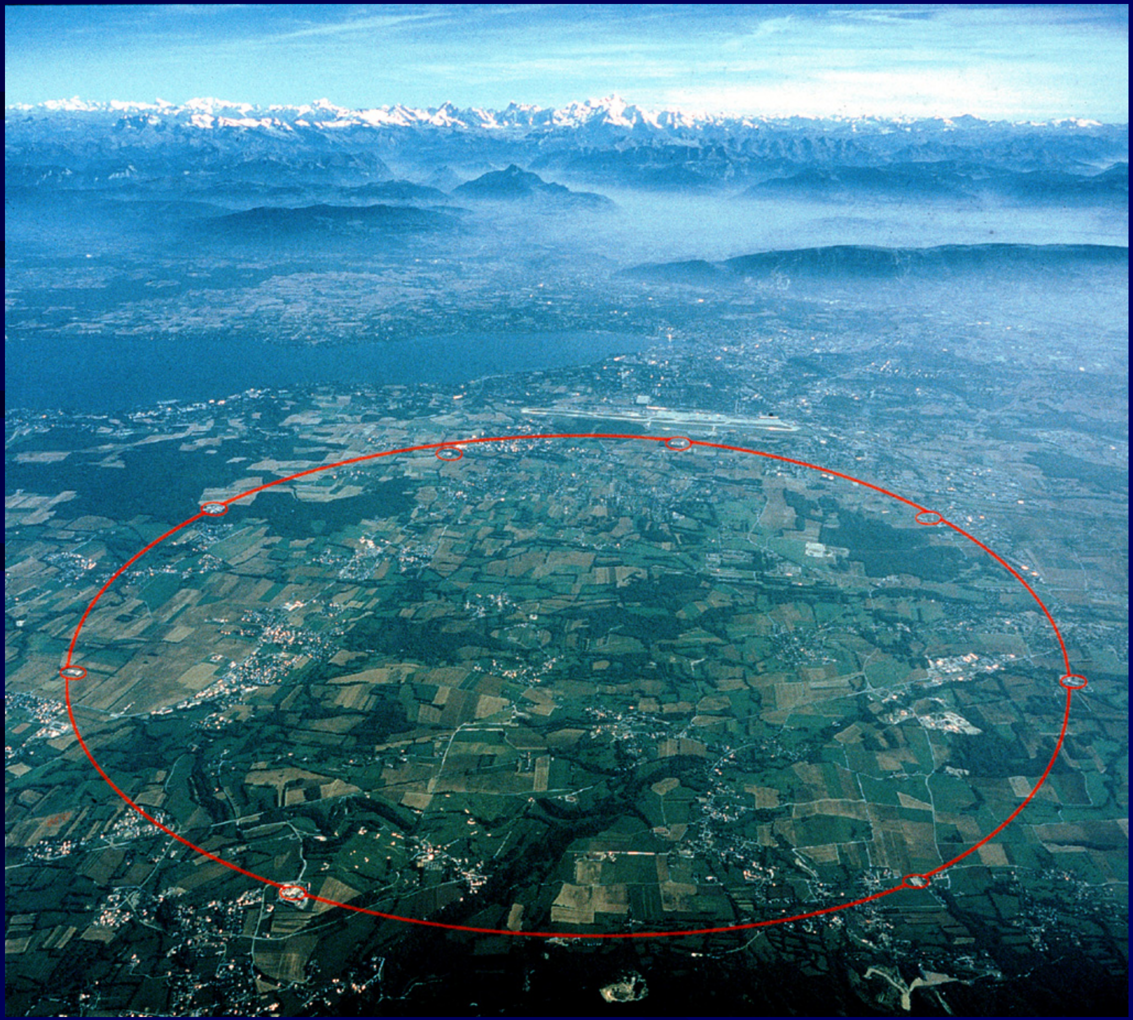
- CERN accelerators
- The source of the problem – beam loss
- Radiation and radioactive substances
- Monitoring
- Impact assessment
- Example (2003)
- Outlook

CERN accelerators (1)



- Linacs
- PSB
- PS
- SPS
- (LHC)
- Experimental Areas
  - ISOLDE
  - AD, LEAR, n-TOF
  - East Hall, West Hall
  - Prévessin site
  - CNGS

CERN accelerators (2)



The source of the problem – beam loss

- High-energy particle beams must interact with matter to generate radiation and to produce radioactive substances:
  - Beam cleaning elements (collimators)
  - Beam extraction elements (kickers…)
  - Targets
  - Detectors
  - Beam dumps

The source - basic difference

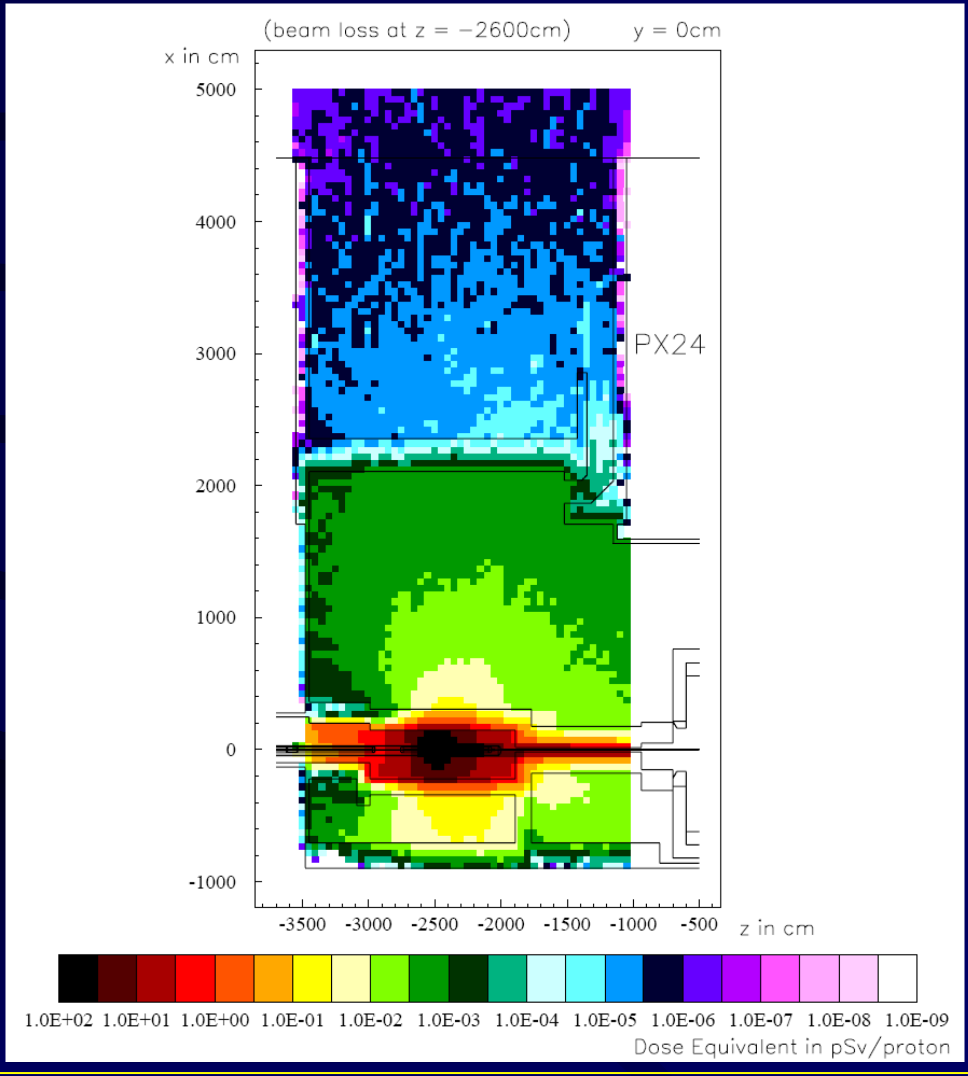
- Hadron machines (p, HI)
  - Nuclear cascades (p, n, n-bar, p-bar, $\pi^{0,\pm}$, K, γ, $e^{\pm}$, $\mu^{\pm}$)
  - Activation of materials
  - Synchrotron radiation negligible
- Example: SPS, LHC

- Lepton machines (e^+e^-)
  - Only electromagnetic cascades (γ, $e^{\pm}$, $\mu^{\pm}$)
  - Synchrotron radiation
  - Activation negligible
- Example: LEP – the clean machine

Stray radiation (1)

- To get into the environment the radiation must pass thick material layers:
  - Shielding structures
  - Earth (for underground installations)
- It must be penetrating
  - Photons (electrons and positrons)
  - Muons
  - Neutrons
- Can be calculated by Monte-Carlo (FLUKA)

Stray radiation (2)



Courtesy of S. Roesler and G.R. Stevenson (CERN)

Stray radiation - photons

- Propagated EM cascade
- Mixture of γ and $e^{\pm}$
- Lower energies replenished by Compton-scattered γ of higher energies
- Up to 10 MeV (neutron shoulder)

Stray radiation - muons

- Progeny of $\pi^{\pm}$
- All energies
- Usually MIP's (~GeV/c)
- Difficult to absorb
- Remain well focused

Stray radiation - neutrons

- From thermal to several MeV
- Scattered
- Activating (e.g. (n,γ) events)

Stray radiation - time structure

- An important constraint for monitoring: Pulsed radiation fields
- Two extreme cases:
  - PS super-cycle: ~0.1 μs each 12 s
  - Collider: train of bunches / several μs between two bunches – quasi-continuous
- Photons and muons practically follow the beam time structure
- Neutrons can be de-synchronized through moderation

Stray radiation – minimization strategy

- Avoid beam losses (accelerator technology, reliability of operation)
- Shielding structures (earth, concrete, iron, marble…)
- Chicanes
- Underground (LHC down to -150 m)

Radioactive substances

- Spallation reactions (neutron-deficit radionuclides, β^+, EC)
- Neutron capture (neutron-rich radionuclides, β^-)
- β/γ emitters, no α (except ISOLDE)
- Beam / target – the higher *Z*, the more species
- Wide range of half-lives
- The shorter the half-live, the higher the activity: $A = \lambda N$
- But too short-lived radionuclides do not reach the environment or have a negligible radiological effect

Radioactive substances

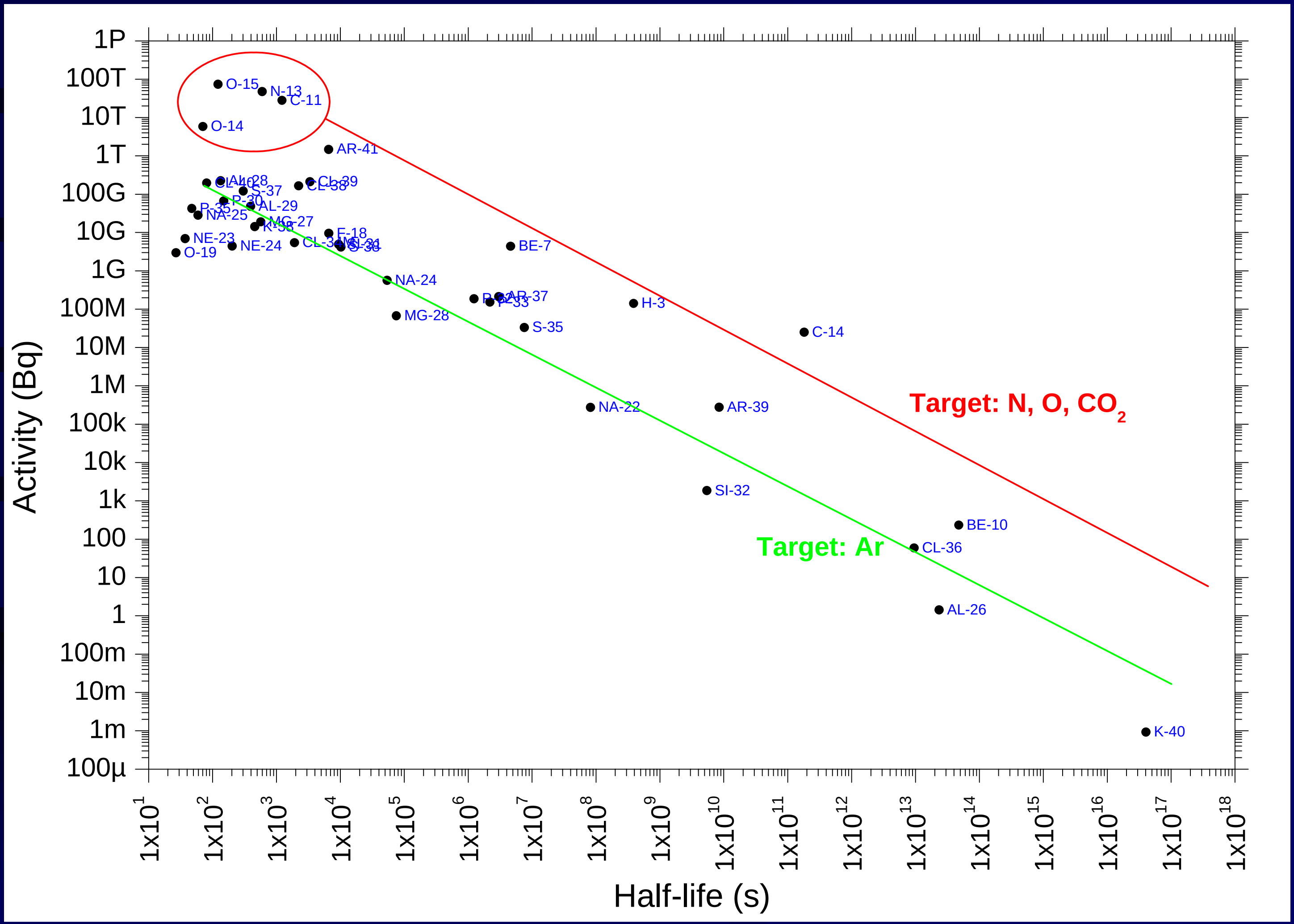
- Carried to the environment by fluids:
  - Air
    - Ventilation of beam areas (cooling by air often needed)
  - Water
    - Water-cooling circuits (usually closed, primary circuits have ion exchangers that trap radioactive ions e.g. ^{7}Be)
    - Water leaks (cannot be 100% excluded)
    - Infiltration water (cannot be 100% avoided)
  - Particles from earth and concrete (transported with fluids)

Radioactive substances – air (1)

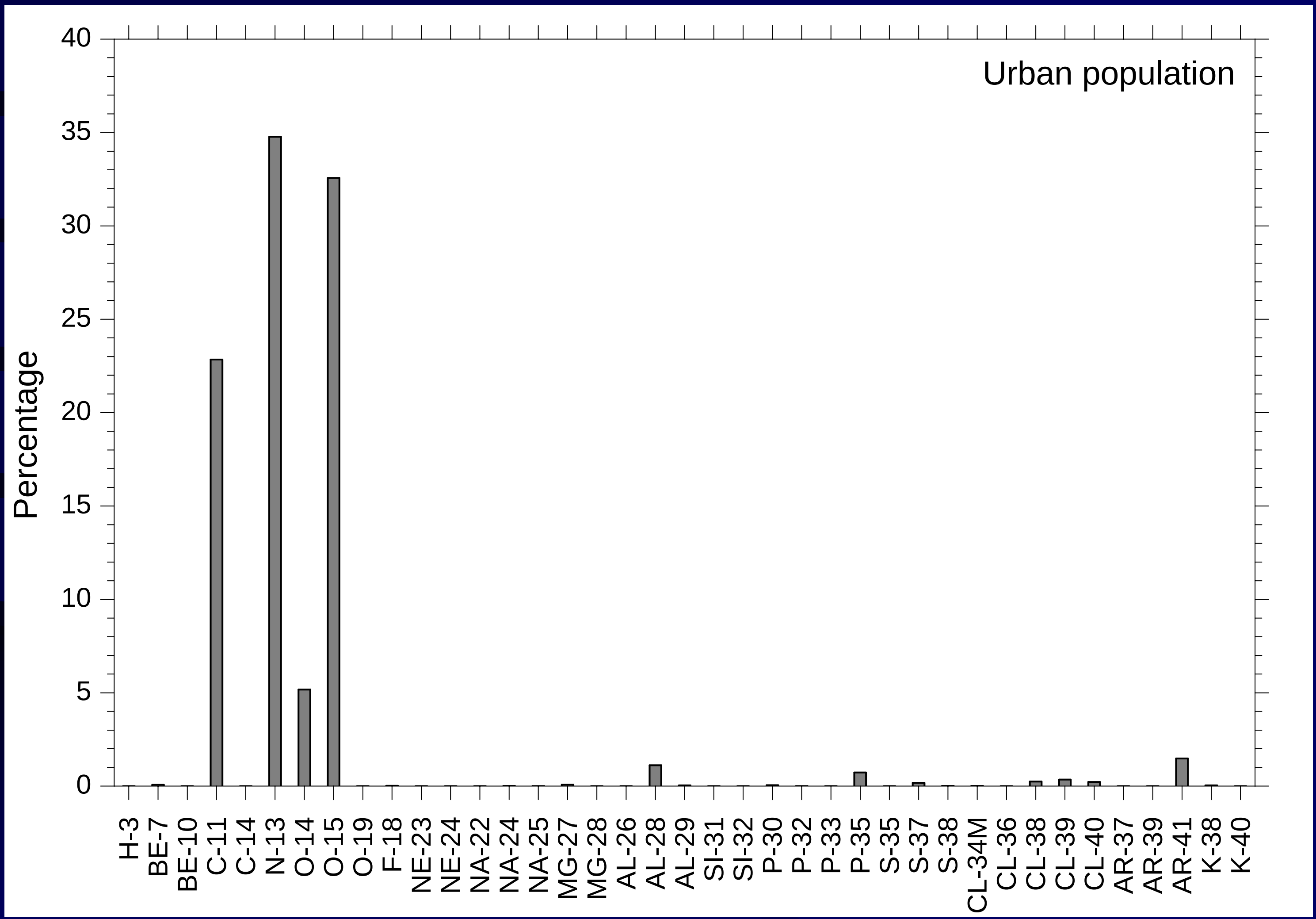
- Direct activation:
  - Targets: O_2, N_2, Ar, CO_2
- Aerosol:
  - As from earth & concrete
  - Will be discussed later

- Dominating short-lived:
  - ^{11}C, ^{13}N, $^{14,15}O$ (β^+)
  - ^{41}Ar (β^-, (n,γ) on ^{40}Ar)
- Dominating longer-lived:
  - ^{7}Be (EC)
  - ^{3}H (HT), ^{32}P, ^{33}P, ^{35}S, ^{22}Na
- Others:
  - ^{10}Be, ^{14}C, ^{19}O, ^{18}F, $^{23,24}Ne$, ^{24}Na, ^{25}Na, $^{27,28}Mg$, $^{26,28,29}Al$, $^{31,32}Si$, $^{30,35}P$, $^{37,38}S$, $^{34m,36,38,39,40}Cl$, $^{37,39}Ar$, $^{38,40}K$

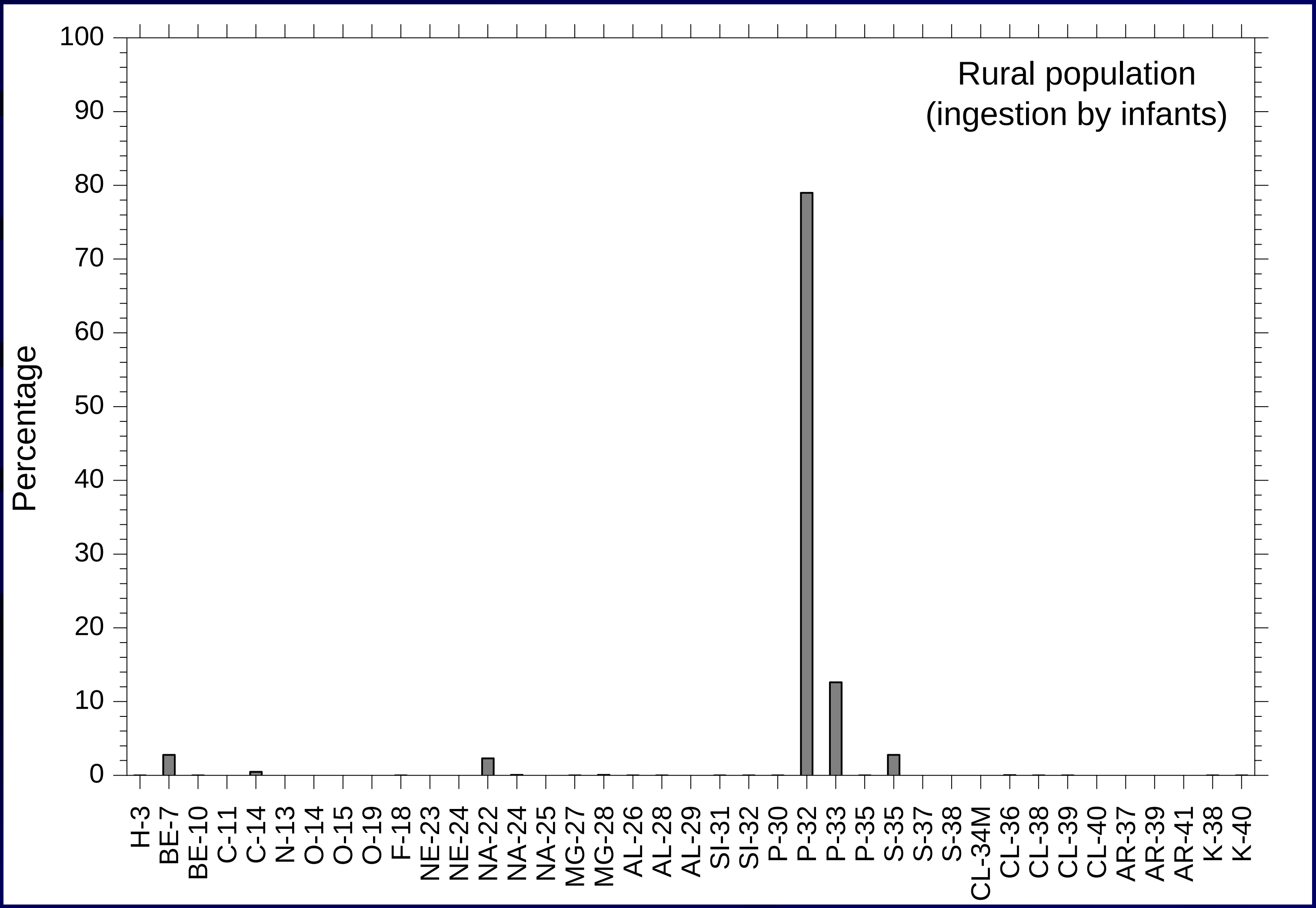
Radioactive substances – air (2)



Air: effective dose breakdown – urban population



Air: effective dose breakdown – rural population



Radioactive substances - water

- Direct activation:
  - Target: H_2O
- Particles:
  - As from earth & concrete
  - Will be discussed later
- Leached:
  - ^{3}H, ^{24}Na, ^{22}Na (soluble)
- Dominating short-lived:
  - ^{11}C, ^{13}N, $^{14,15}O$ (β+)
- Dominating longer-lived:
  - ^{3}H (HTO)
  - ^{7}Be (EC)

Radioactive substances - particles

- Targets with high *Z* available
- Interplay between mobility and half-life
- Selection
- Sometimes species one would not expect

- ^{3}H, ^{7}Be,
- ^{22}Na, ^{24}Na
- ^{46}Sc, ^{48}V, ^{54}Mn,
- ^{56}Co, ^{57}Co, ^{58}Co, ^{60}Co
- ^{65}Zn
- ^{134}Cs
- ^{152}Eu

Except for ^{3}H, activity densities are 2-3 orders of magnitude below that of ^{7}Be but still to be considered.

Radioactive substances - ISOLDE

- Uranium & Thorium carbide targets
  - High-*Z* targets → produce anything you can imagine
- Emanating alpha activity ($^{220}Rn \rightarrow {}^{212}Pb$)
- Emanating iodine (^{124}I, ^{125}I, ^{126}I, ^{131}I)
- Noble gases captured from vacuum pumps (^{42}Ar, ^{85}Kr, ^{127}Xe, ^{129m}X, ^{131m}Xe, ^{133}Xe)

Air – minimization strategy

- Avoid beam losses
- Avoid development of nuclear cascades in air
  - Solid matter shielding (iron, marble…)
  - Helium balloons (low-*Z* target)
- Semi-closed cooling circuits
  - Decay of short-lived
  - Pre-cleaning of aerosol
- HEPA filters at the end of the ducts

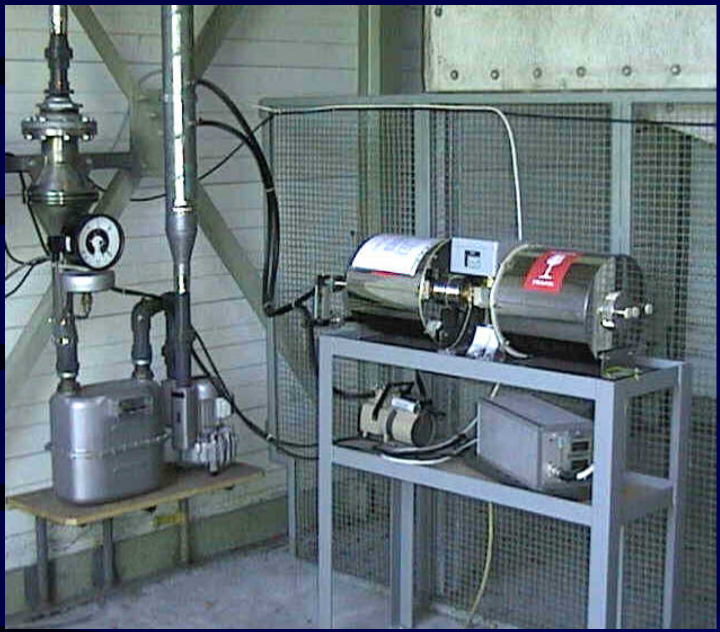
Water – minimization strategy

- Closed cooling circuits equipped with ion exchangers close to hot areas (only HTO remains)
- Construction in geological layers impermeable to water (molasse)
- Concrete with layers impermeable to water
- Avoid draining over concrete (metallic pipes)
- Cover the facility against rain
- Hydro-geological study before the project starts

Monitoring – main components

- Monitoring of releases of radioactive substances (air, water)
- Monitoring of stray radiation
- Measurement of activity densities in environmental matrices
- Assessment of the ecological and radiological impacts

Monitoring - 9 ventilation stations (1)



- Differential ionization chamber
  - Short-lived radioactive gases
  - ^{11}C, ^{13}N, ^{14}O, ^{15}O, ^{41}Ar
  - Online readout
- Aerosol sampler
  - Analyzed offline
  - ^{7}Be, ^{22}Na, ^{46}Sc, ^{48}V, ^{54}Mn, ^{60}Co…
- Ventilation flow-rate sensor
  - Online readout
- Monthly balance sheets of released activity

Monitoring - 9 ventilation stations (2)

- Tritium: Conservative estimates based on
  - Maximum ^{3}H activity densities measured (HTO, HT)
  - Air amounts released
- ISOLDE:
  - Exchange of UC and ThC targets – short-term operations with alpha emanation
  - Emptying of reservoirs with pump gases
  - Screening of total alpha on aerosol
  - Lucas cell and decay curve analysis

Monitoring - 5 water monitoring stations

- At the end of drainage networks
- Water monitor
  - NaI(Tl) probe in a water tank
  - For short-lived (^{11}C, ^{13}N, ^{24}Na)
  - Online readout
- Automatic water sampler
  - Analyzed offline
  - ^{3}H, ^{7}Be, ^{22}Na, total beta
- Water flow-rate sensors
- Monthly activity density sheets
- Annual releases

Monitoring - stray radiation

- Two kinds:
  - Gamma and penetrating charged particles (μ)
  - Neutrons
- Two instruments
  - Pressurized ionization chamber
  - Rem-counter
- Calibrated for $H^*(10)$
- Online readout
- Quarterly integration
- 40 stations completed with
- about 200 ^{6}LiF/^{7}LiF TLD

Monitoring - environmental samples

High volume aerosol sampler
600 m³/h
Filter exchanged once a week

- 9 aerosol sampling stations
  - Filters exchanged twice a month
- 4 grass/soil sampling places
  - Annual collection (late summer)
- 2 precipitation collectors
  - Monthly collection (precipitation rate online)
- 6 sampling points in rivers
  - Annual (late summer)
  - Water
  - Sediment
  - Bryophytes
- 5 groundwater wells
  - Annual (autumn)
- Agricultural products
  - According to availability: colza, asparagus, wheat, sunflower, wine

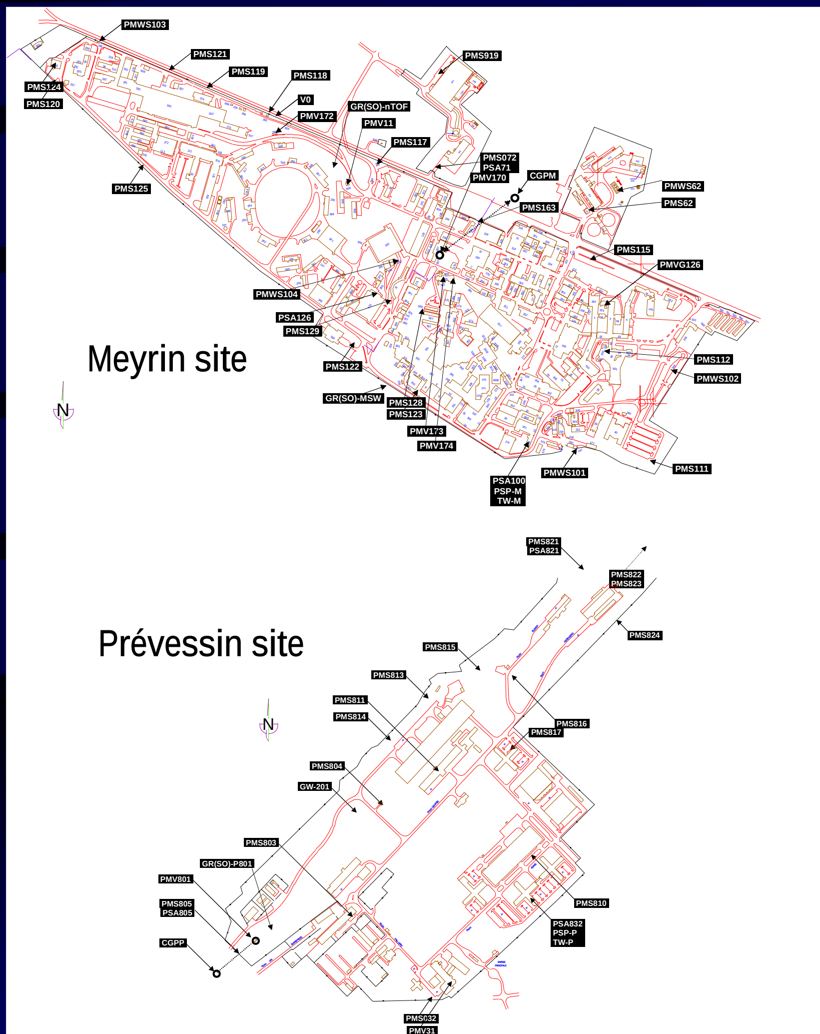
Monitoring – environmental laboratory

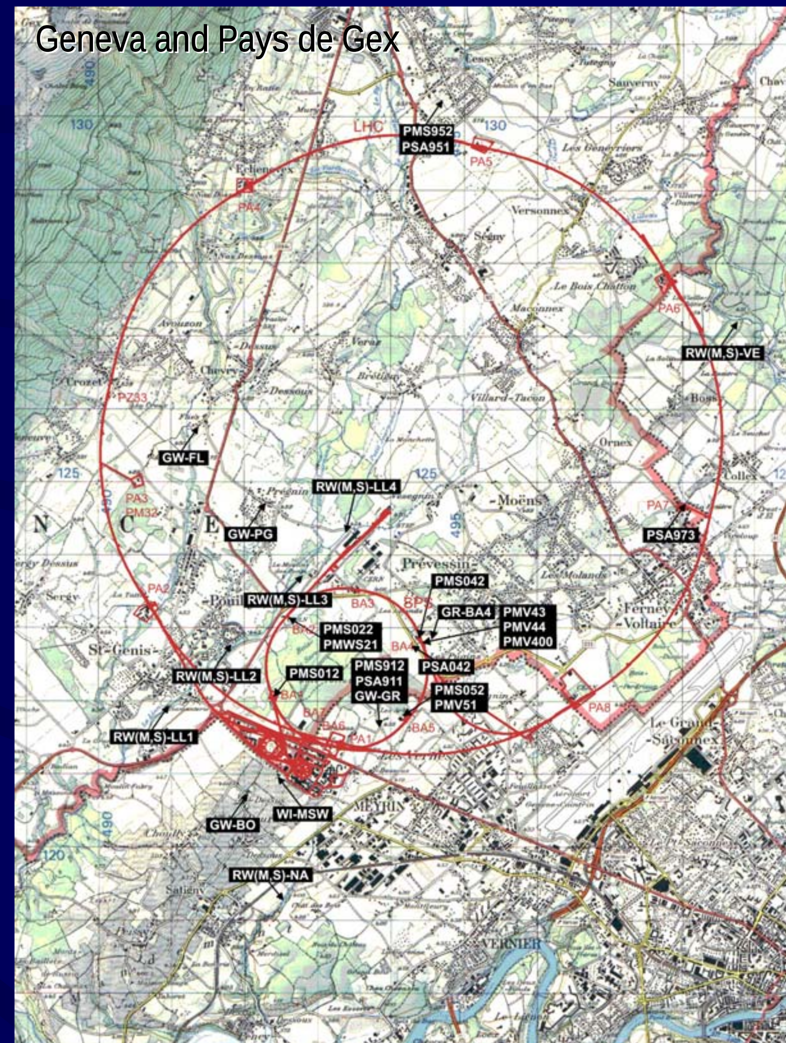
- Optimized for β/γ analyses (+ α screening for ISOLDE)
- Gamma spectrometry
  - 4 HPGe detectors (up to 52% SLL)
  - Genie 2000
- Total α/β counting
  - Proportional counter with automatic sample changer (Eberline FHT770GR)
- Liquid scintillation counter (^{3}H)
  - Packard TRICARB 3700 TR
  - MDA: 1.6 Bq/l, customized DE software
- Auxiliary equipment
  - 4 water evaporators, flame photometer for [K^{+}], 2 drying ovens, distillation apparatus…

Detection limits

- Release monitors:
  - Short-lived gases in ventilation: ~10 kBq/m^3
  - Water (Bq/l):
    - ^{11}C, ^{13}N: 1.6
    - ^{24}Na: 3.0
- Laboratory:
  - Aerosol (µBq/m^3):
    - Total β: 25
    - ^{7}Be: 60
    - ^{22}Na, ^{60}Co, ^{137}Cs: <4
  - Aerosol HVS (µBq/m^3):
    - ^{7}Be: 7
    - ^{22}Na, ^{60}Co, ^{137}Cs: <0.5
  - Water (Bq/l):
    - Total β: 0.014
    - ^{3}H: 1.6
    - ^{7}Be: 2
    - ^{22}Na, ^{60}Co, ^{137}Cs: <0.2

Monitoring - spatial extent





Impact assessment – ecological

- Environmental samples:
  - Comparison with Swiss immission limits for air and water (ORaP)
  - Comparison with Swiss exemption limits for other matrices (grass, soil, sediment, bryophytes…, ORaP)
- Agricultural products:
  - Comparison with Swiss food limits (OSEC)

Impact assessment – radiological (1)

- Expressed in terms of effective dose to members of the public
- CERN Radiation Safety Manual:
  - Guideline value related to source: 0.3 mSv/a
- Critical groups of the population:
  - Meyrin Site: Border guards
  - Prévessin Site and SPS: Waste dump workers
  - Water releases: People making use of water from the rivers Nant d'Avril (CH) and Le Lion (F).

Impact assessment – radiological (2)

- Stray radiation:
  - Directly from the readings of the stray radiation monitors assuming suitable occupancy factors
- Releases of radioactive substances:
  - Methodology based on:
    - HSK-R-41 (mainly air)
    - IAEA Safety Report No. 19 (additional exposure pathways added to those assumed in HSK-R-41)
    - ICRP 72
  - Computer code available
  - Weather statistics from the airport Geneva Cointrin (72 wind direction sectors, 20 wind speed bins, 6 stability classes)

Impact assessment – radiological (3)

- Air releases
  - Scenarios
    - Short-term actual release
    - Short-term hypothetical release for release limit calculation
    - Short-term accident
    - Long-term chronic release
  - Exposure pathways
    - External from radioactive plume and ground deposition
    - Inhalation
    - Ingestion (fruits and vegetables, meat, dairy products)

Impact assessment – radiological (4)

- Water
  - Scenarios
    - Release into a river + field irrigation
    - Release into a sewage treatment plant
  - Exposure pathways
    - External from immersion in the river water and from sediment or sludge
    - Drinking of water and ingestion of fish from the river
    - Ingestion of food (watered animals, irrigated fields, as for air)
    - External on irrigated fields, inhalation on irrigated fields
    - Inhalation of re-suspended sludge
    - Fertilization of fields with sludge (F), burning of sludge (CH)

Impact assessment – radiological (5)

- External exposure from radioactive plume dominates → special attention in the model
- Space integral of the dose kernel from Gaussian plume including conversion from the dose absorbed in air to the *effective* dose

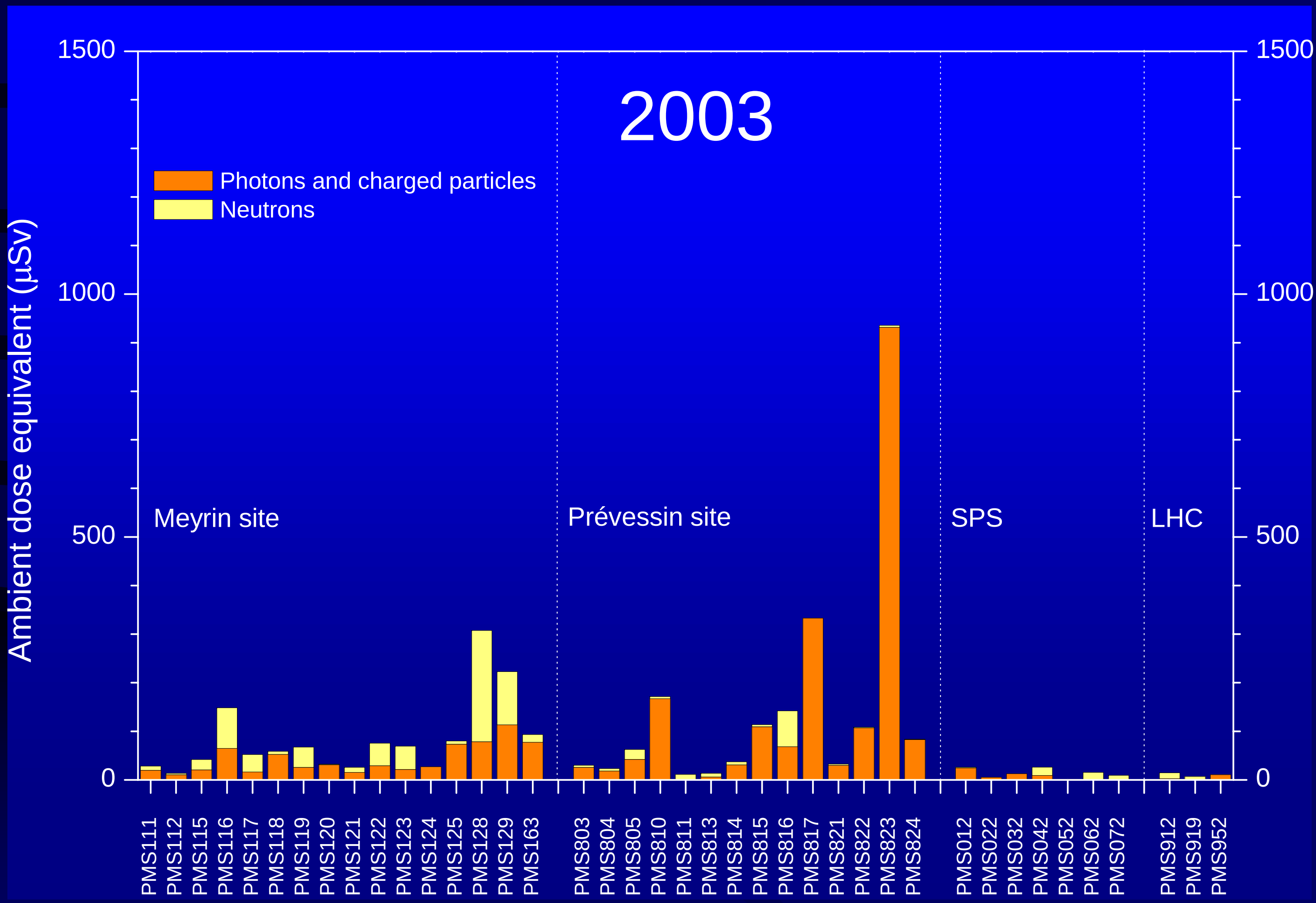
$$D_\gamma = Q\frac{\varepsilon}{\rho_{\mathrm{air}}}\frac{1}{4\pi}\sum_i e_{\mathrm{kerma}}(E_i)\mu_{\mathrm{a},i}E_iY_i\int\frac{B(E_i,\mu_i r)\exp(-\mu_i r)\chi(\mathbf{r})}{r^2}d^3\mathbf{r}$$

Impact assessment – radiological (6)

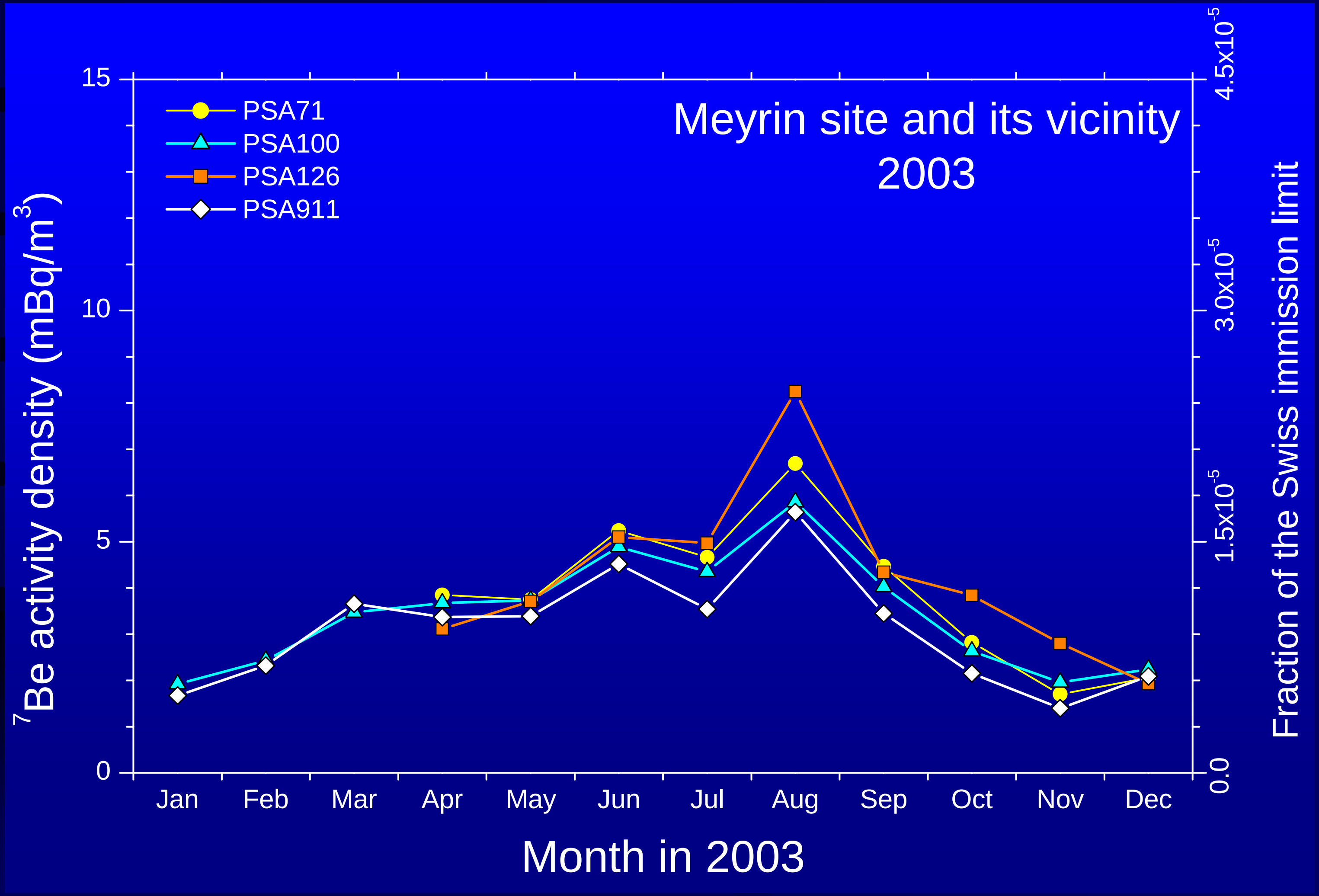
$$\int \frac{e^{-\mu r} f(\mathbf{r})}{r^2} d^3\mathbf{r} \longrightarrow dP/dr = \mu e^{-\mu r} \longrightarrow \frac{2\pi}{\mu} \frac{1}{N_0} \sum_{i=1}^{N_0} f(\mathbf{r}_i)$$

- Monte Carlo integration with biased sampling of distance to volume elements $d^3\mathbf{r}$
- Random sampling of weather situations (for long-term releases) according to the weather statistics
- Resembles an analog Monte Carlo simulation

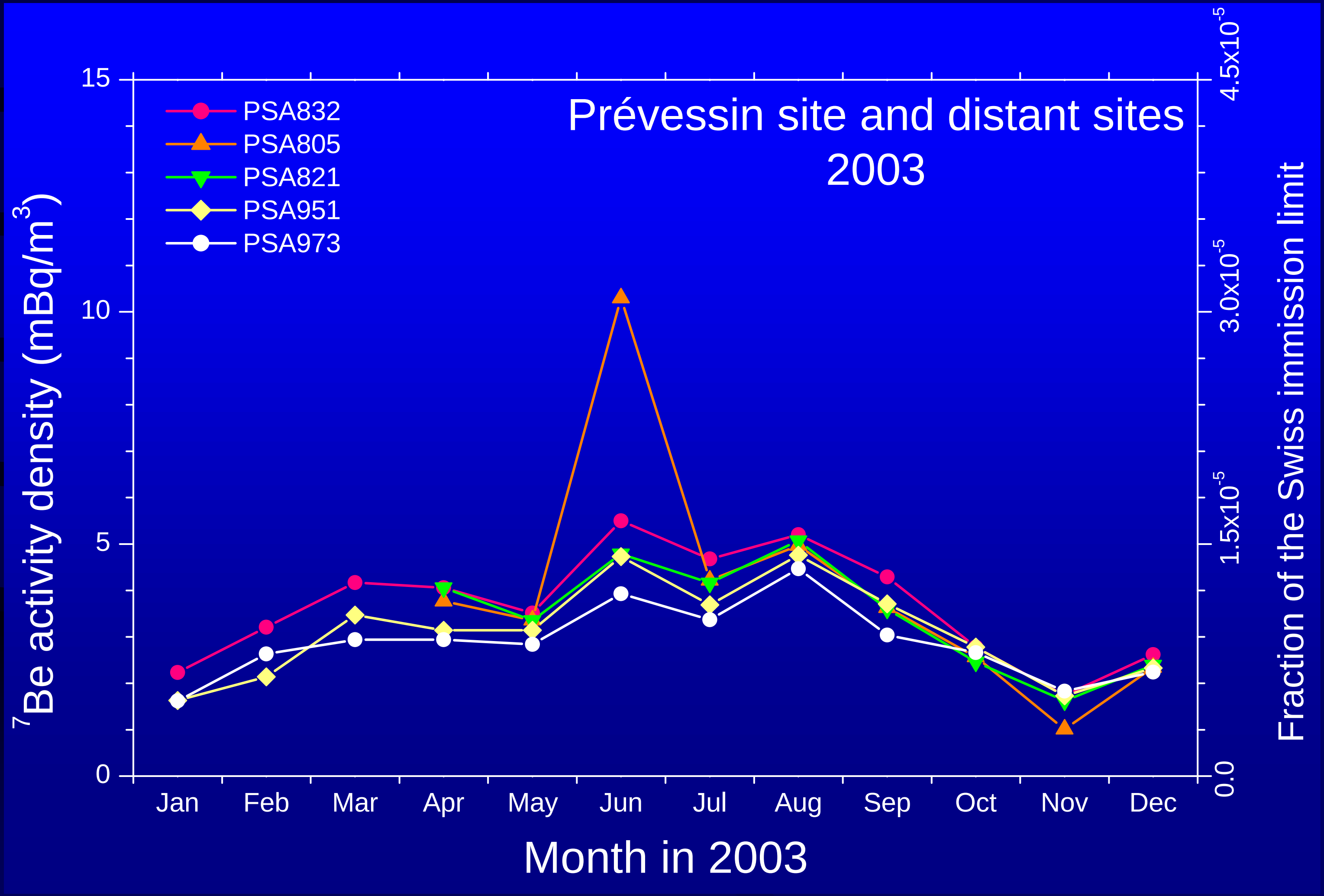
Example – net doses in 2003



Example – ^{7}Be in aerosol in 2003 (1)



Example – ^{7}Be in aerosol in 2003 (2)



Example – river bryophytes in 2003

Bq/kg dry weight

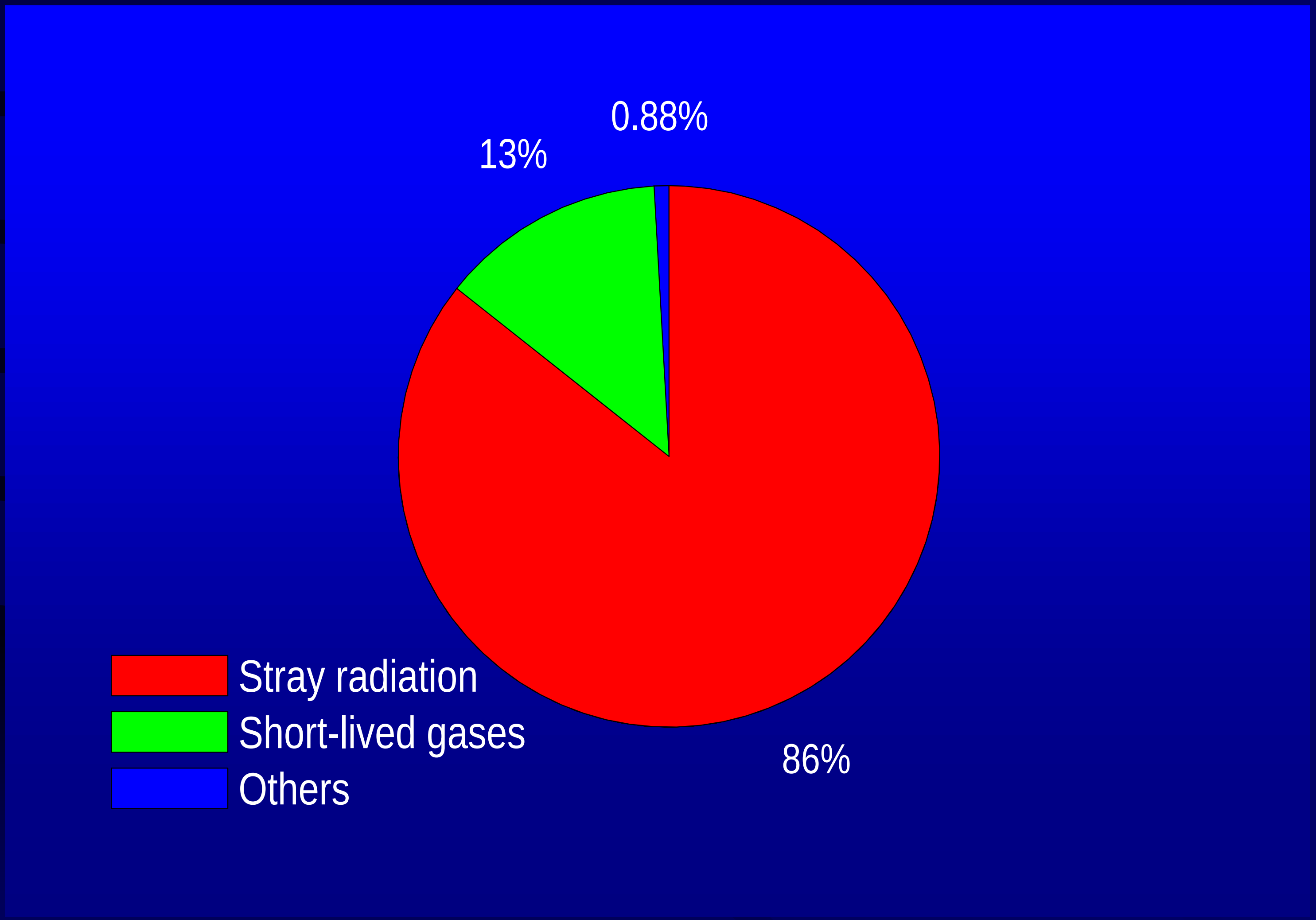
Reference river ↓

Sample	LL1	LL2	LL3	LL4	NA	VE
River		Le Lion (F)			Nant d'Avril (CH)	Versoix (CH)
Date	19/09/2003	18/09/2003	18/09/2003	19/09/2003	18/09/2003	18/09/2003
^{7}Be	1470 ± 70	300 ± 20	340 ± 20	180 ± 30	280 ± 20	380 ± 30
^{54}Mn	12 ± 2	97 ± 3	< 0.5	< 3	< 2	< 2
^{60}Co	< 1	2.1 ± 0.6	< 0.6	< 4	< 1	< 2
^{137}Cs	16.7 ± 0.8	11 ± 2	7.1 ± 0.7	7 ± 4	14 ± 2	6 ± 2

Releases and effective doses in 2003

Radionuclide category	*R* (GBq)	*D* (Sv/Bq)	*E* (µSv)	*R* (GBq)	*D* (Sv/Bq)	*E* (µSv)
Air releases	*Meyrin site*			*Prévessin site*		
Tritium (water vapour)	170	5.7E-20	0.0097	17.0	3.8E-19	0.0065
^{7}Be (aerosol)	0.30	1.9E-17	0.0056	0.017	1.6E-16	0.0028
Short-lived gases (^{11}C)	9600	3.4E-19	3.3	1380	5.5E-19	0.76
Other beta/gamma (^{60}Co)	0.0100	1.5E-14	0.15	0.00073	1.2E-13	0.088
Radioactive iodine (^{126}I)	0.0103	5.6E-16	0.0058	-	-	-
Alpha emitters (^{212}Pb)	0.0076	4.3E-16	0.0032	-	-	-
Total from emissions			*3.4*			*0.86*
Water releases	*Nant d'Avril*			*Le Lion*		
Tritium (HTO)	6.3	9.5E-20	0.00060	38	9.5E-20	0.0036
Other beta/gamma (^{22}Na)	0.041	7.1E-16	0.029	0.053	7.1E-16	0.037
Total from water releases			*0.030*			*0.041*
Stray radiation			*21*			*14*
Total from all sources (rounded)			25			15

Effective dose breakdown



Outlook - on the way

- LHC: unprecedented beam intensity and energy
  - 2 beams with 7 TeV protons
  - 350 MJ of stored energy per beam
- RAMSES project
  - PIPS chambers for short-lived radioactive gases (DL of ~ 1 kBq/m^3)
  - Water monitors with spectroscopic analysis
  - Ultrasonic anemometers
  - State-of-the-art data acquisition
- LHC & CNGS: Number of stations and samples will be doubled.

Outlook – future accelerators

- CLIC – Compact Linear Collider (clean like LEP)
- Future challenges:
  - Neutrino factories: hadron beams of MW power
  - Muon colliders
    - Exposure from neutrinos (!)
    - Critical groups of the population at long distances from the source
    - Neutrino dosimetry (!)