Fluka calculations for the shielding design of the Linac4 beam dump at CERN

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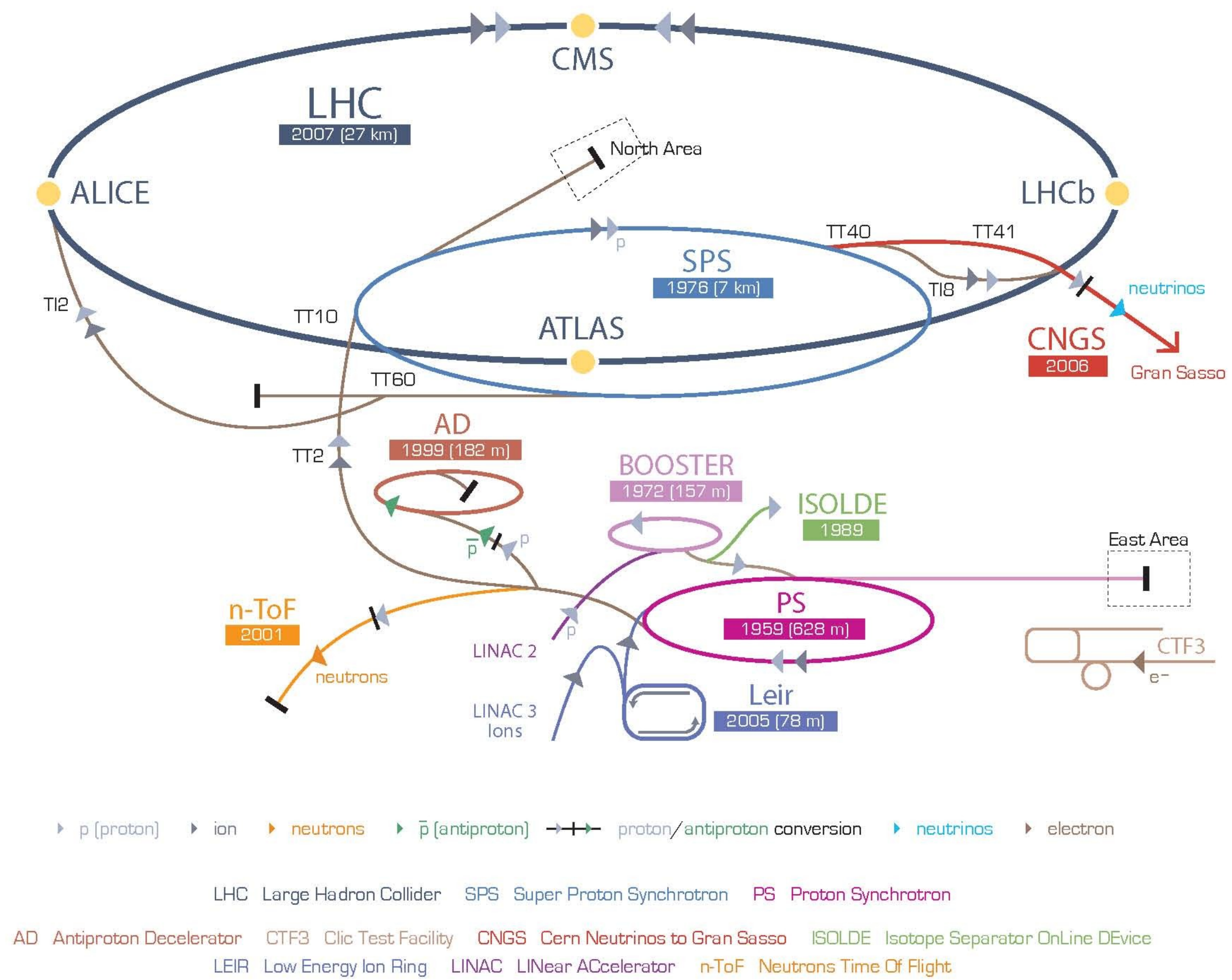
Overview

- Introduction - Linac4 accelerator at CERN
- Study objectives
- Fluka geometry description
- Scored quantities for the radiation protection evaluation
- Conclusions and gained experience

CERN accelerator complex

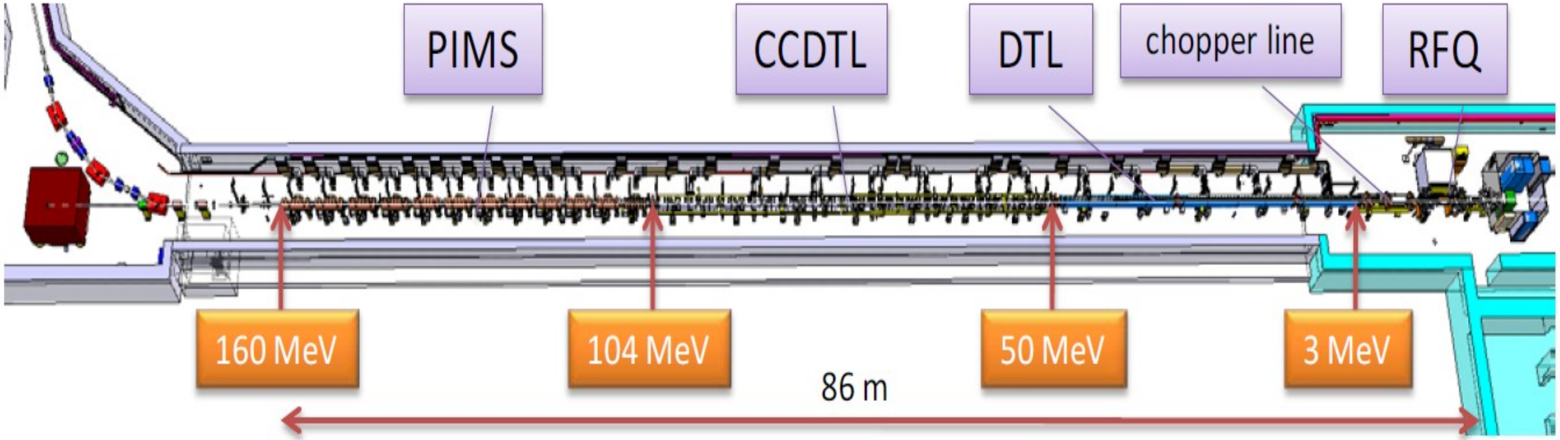


Linac4 accelerator

To fully exploit LHC potential, the present injector to PS Booster Linac2 will be replaced by Linac4, which will provide higher intensity and improve long term reliability

Linac4 is a 160 MeV H- linear accelerator consisting of:

- Pre-injector (source, magnetic LEBT, 3 MeV RFQ, chopper line)
- Three types of accelerating structures, all at 352 MHz
- Beam dump at linac end, switching magnet towards transfer line – PS Booster
- Beam measurements at linac end and at PS Booster entrance



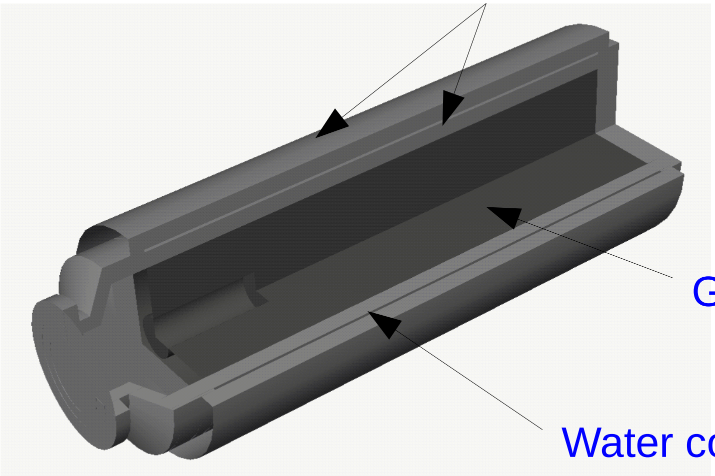
	Energy [MeV]	Length [m]	RF power [MW]	Focusing
RFQ	0.045 – 3	3	0.6	RF focusing
DTL	3 – 50	19	5	112 perm. quads
CCDTL	50 – 102	25	7	21 EM quads
PIMS	102 – 160	22	6	12 EM quads

Linac4 will be ready for connection to the PS Booster at the end of 2017

Linac4 dump

Linac4 is terminated by a dump collecting the beam during its commissioning phase, measurement operation as well as in case of degraded situation

Dump design and its fluka implementation:



160 MeV H- beam interacting with the dump produces mixed radiation fields with large numbers of neutrons and highly penetrating particles

-> need to have an effective shielding to limit activation of the surrounding structures and protect personnel accessing the machine

Study objective and method

The aim of this study is to determine an optimal shielding fulfilling the radio-protection requirements

The proposed shielding must take into account:

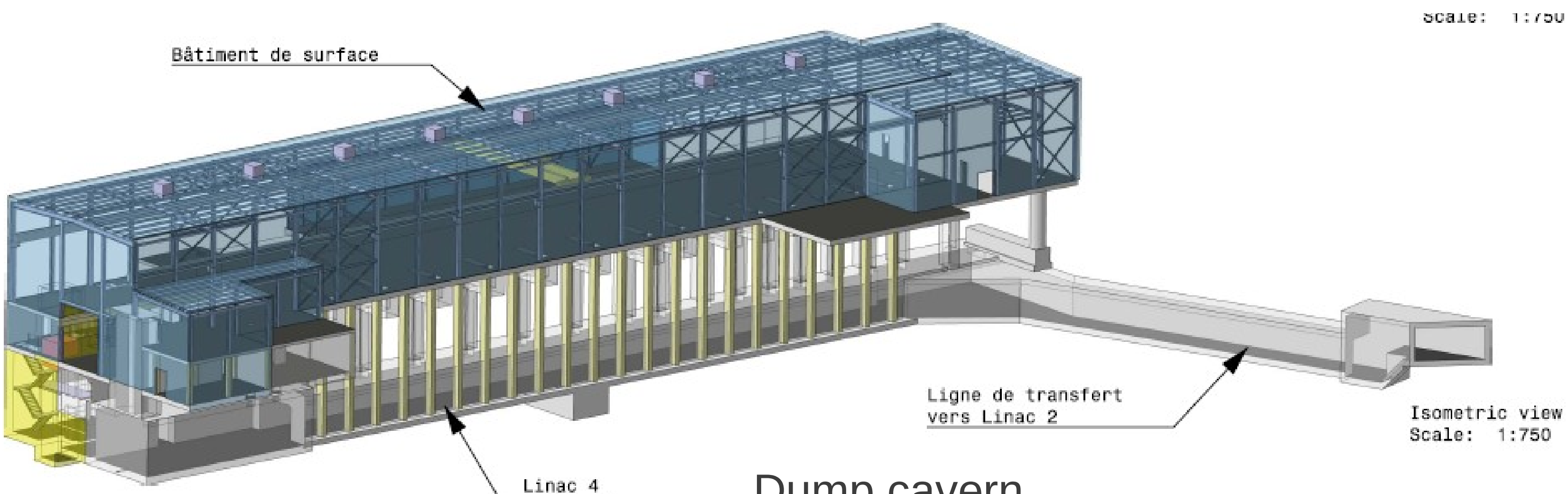
- Different accelerator operational phases
- The space constraints inside the accelerator vault
- The decommissioning of the installation at the end of its lifetime

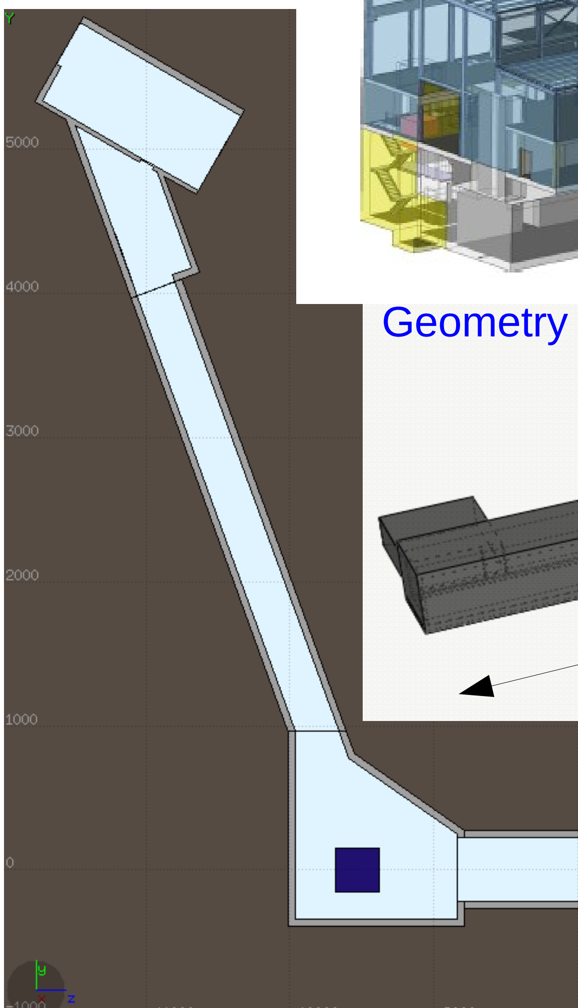
FLUKA calculations has been performed to evaluate the relevant physics quantities:

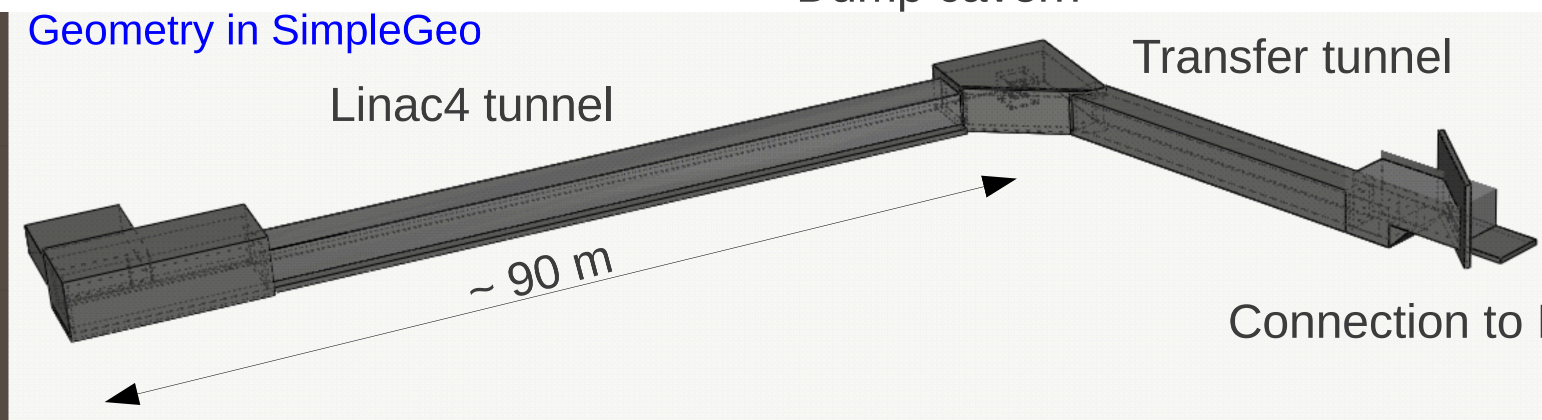
- Particle fluencies and neutron energy spectra
- Residual and prompt dose rates
- Induced activation of the dump and shielding
- Airborne radioactivity and cooling water activation

All above has been done for different irradiation profiles, cooling times and shielding geometry and material combinations

Fluka geometry – civil engineering

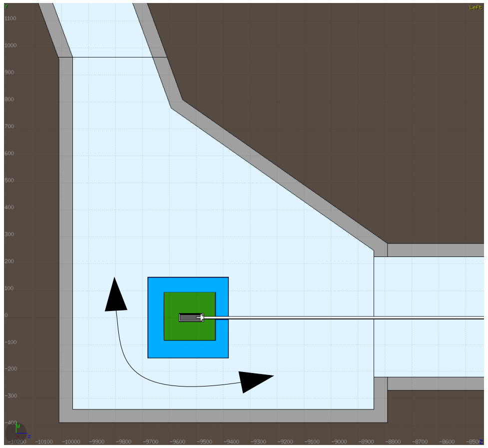






N.B. Linac2 area will be accessible during the Linac4 commissioning and reliability runs

Shielding design



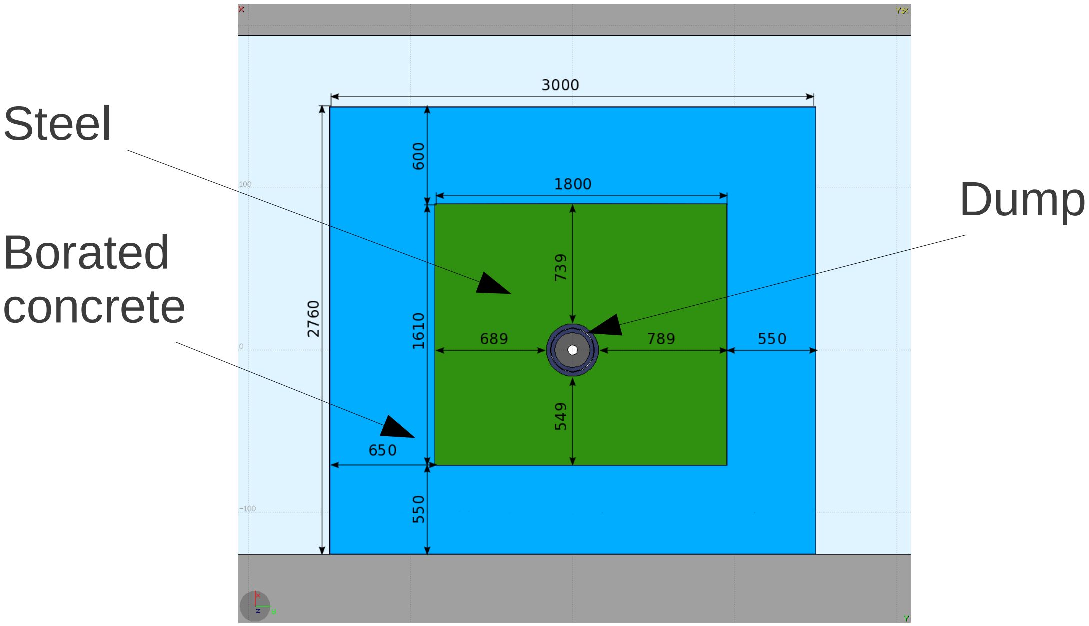
Transport area

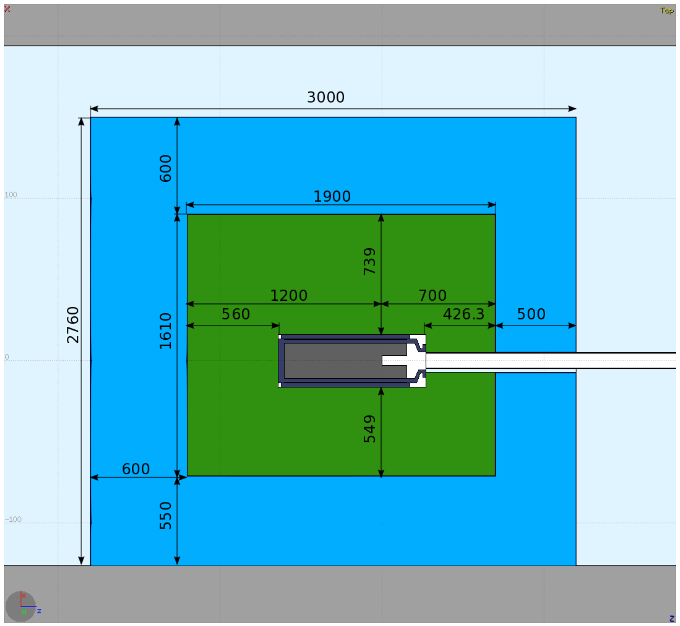
Constrains:

- Limited space for shielding to keep passage around the dump
  -> overall dimension is 3x2.76x3 m3
- Keep induced activity and residual dose reasonably low
  -> short cooling times in case of intervention

Proposed shielding:

- Several shielding configuration tested (different materials, geometry) using a cylindrical geometry and taking benefit of the symmetry (USBIN cylindric allows proper statistics in short time)
- Final configuration consists of steel surrounding the dump and borated concrete used as outermost layer





Shielding materials

Standard materials used for the dump (pure carbon and stainless steel 316LN) and first part of the shielding. The second part is made from borated concrete of the following compositions:

Chemical element	Mass fraction [%]
Hydrogen	0.96
Oxygen	51.3
Boron	2.9
Carbon	5.36
Magnesium	0.42
Aluminum	0.79
Silicon	15.7
Sulfur	0.42
Calcium	23.0
Iron	0.5

N.B. Standard composition of the borated concrete taken from:

V. Khripunovl, R. T. Santoro, H. Y. Khater, "Profit from Borating Concrete in the ITER Biological Shield", 17th IEEE/NPSS Symposium. (1997) [Link]

Volume and weight:

Material	Density [g/cm3]	Volume [m3]	Weight [tons]
Dump	5.12	0.07	0.34
Steel	7.80	5.50	43
Borated concrete	2.43	19.33	47

Total weight (dump + shielding): ~90.2 tons

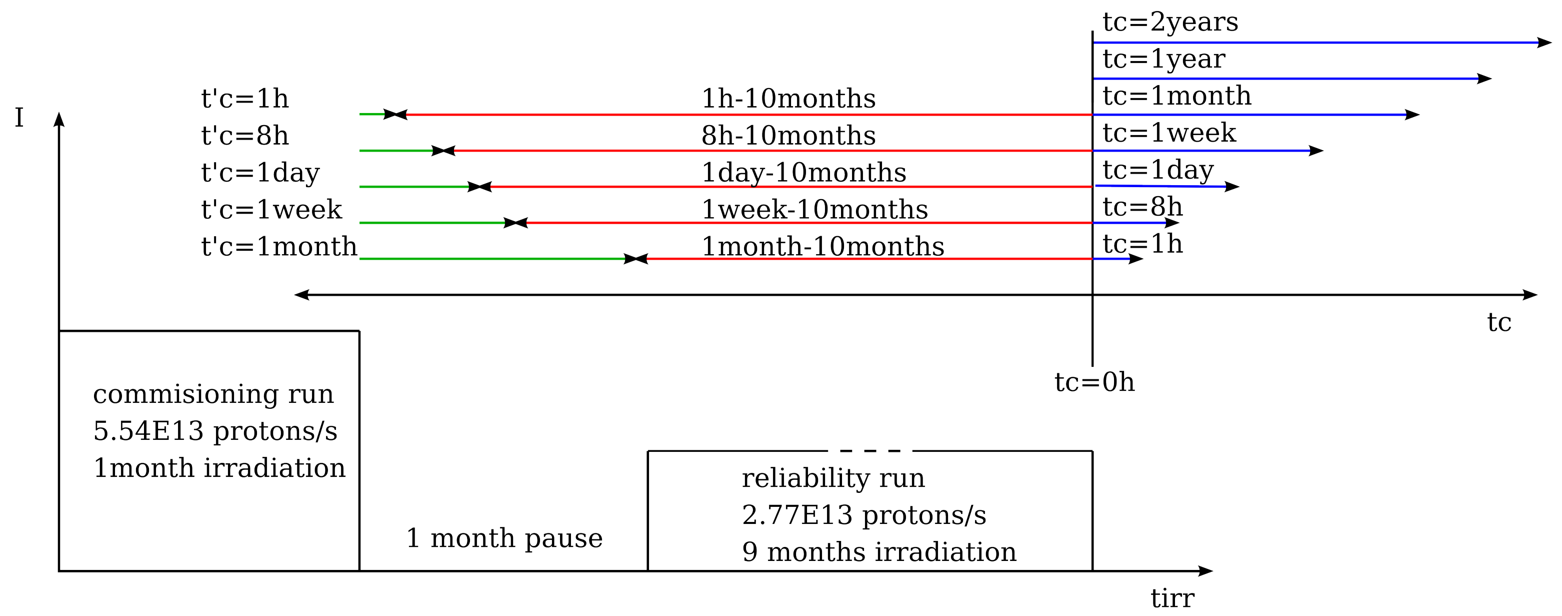
Operation scenarios/irradiation profile

EDMS 1184637

	pulse current and duty cycle	*spot size (mm x mm)*	*duration*
Commissioning	40 mA 400microsec 1.11 Hz (0.04%)	6 x 8	~1month (12hour/day)
Reliability Run	20 mA 200microsec 1.11 Hz	6 x 8	6-9 months (24hour/day)
PSB Operation	40 mA 400microsec 1.11 Hz (0.04%)	3 x 6	Occasionally

Table 3: Details of the three phases of dump use.

Irradiation profile in Fluka:



N.B. : Beam 160 MeV protons, nominal beam power 2.84 kW

Physics setting and scored quantities

Physics and transport setting:

- DEFAULTS: precisio
- PHYSICS: new evaporation model, no heavy fragment evaporation
- LOW-NEUT: n-groups 260, Emax = 20 MeV
- THRESHOL card: kinetic energy threshold for stars set to 20 MeV
- PART-THR: 10 keV energy trasport cut-off set all particles except for neutrons
- EMFCUT: transport energy cut-off is set to 100 keV for e+e- and 50 keV for photons, setting adapted with RADDECAY card
- EMF: - on for activation studies
  - off for computation of prompt dose

Biasing:

- Region importance biasing used to improve the statistic

Scored quantities:

- Fluence for different particles
- Neutron energy spectra
- Dose equivalent for prompt (Linac2 area)
- Residual radiation (access to tunnel when beam off)
- Radionuclides yield
- Particle track-length

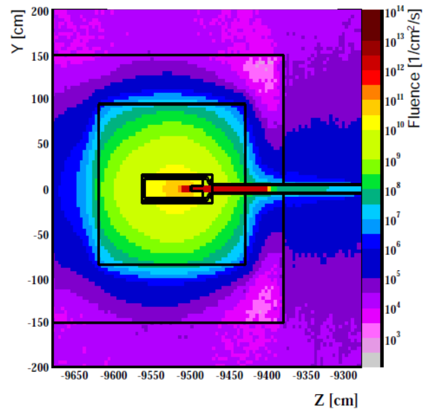
Particle fluence 1/2

Method:

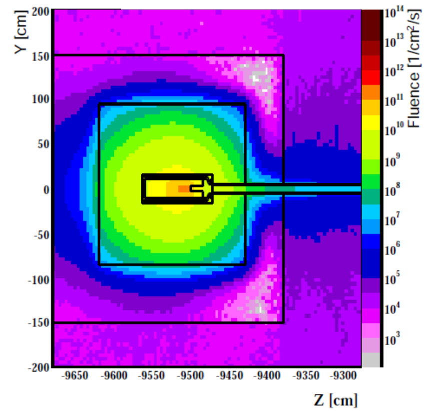
- 2 USRBIN cards using a Cartesian mesh
- various particles scored: photons, protons, neutrons, all particles
- different regions of interest: inside the dump and its shielding, inside the dump cavern, inside the transfer tunnel
- Plotting of result done by a routine base on ROOT (all plots in this talk)

Results:

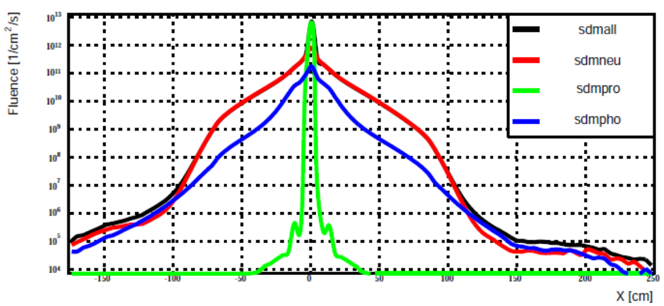
All particles



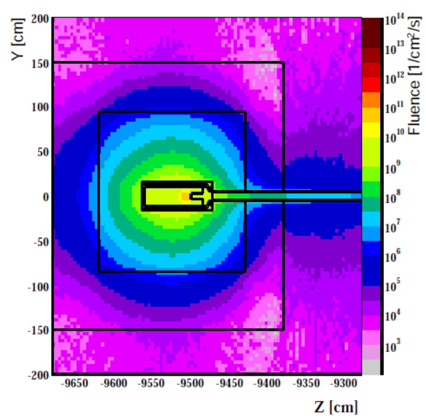
Neutrons



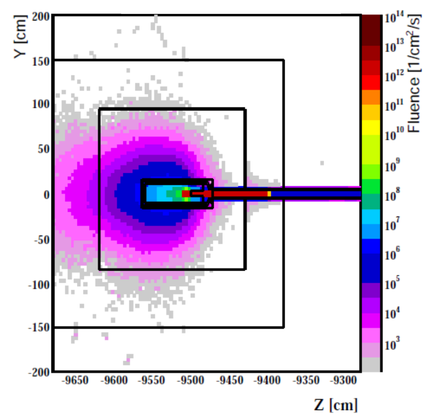
Fluence along X axis



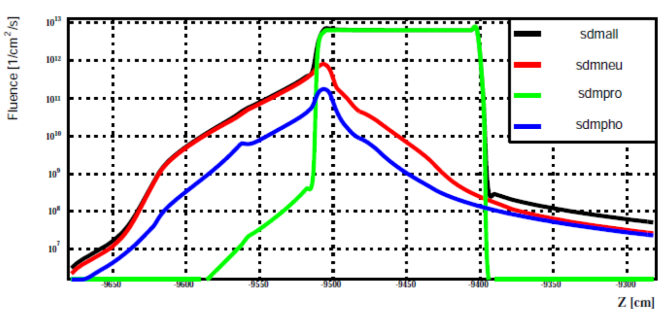
Photons



Protons



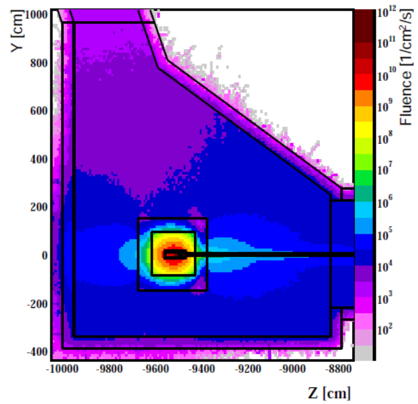
Fluence along Z axis



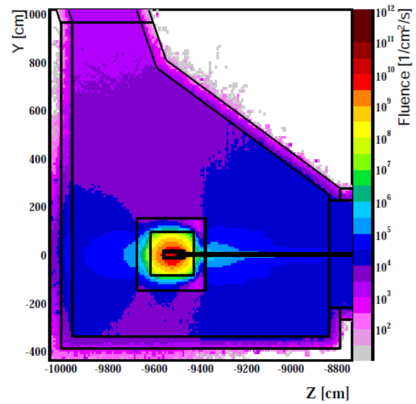
Particle fluence 2/2

Fluence maps for the dump cavern

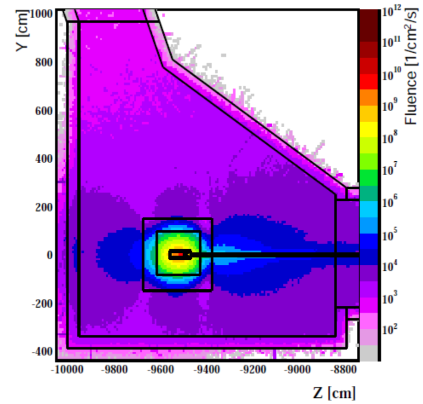
All particles



Neutrons

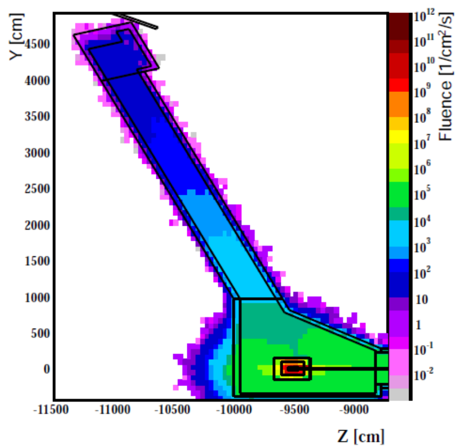


Photons

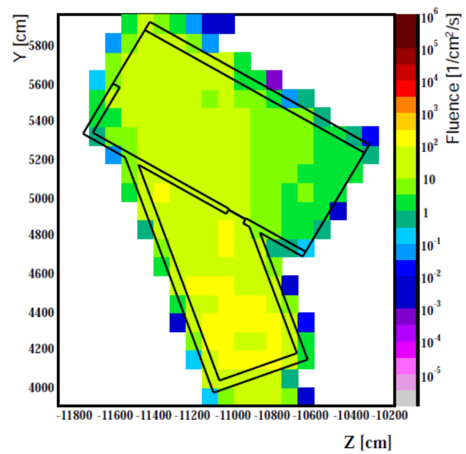


Fluence maps for the transfer tunnel

Linac4 level



Linac2 level



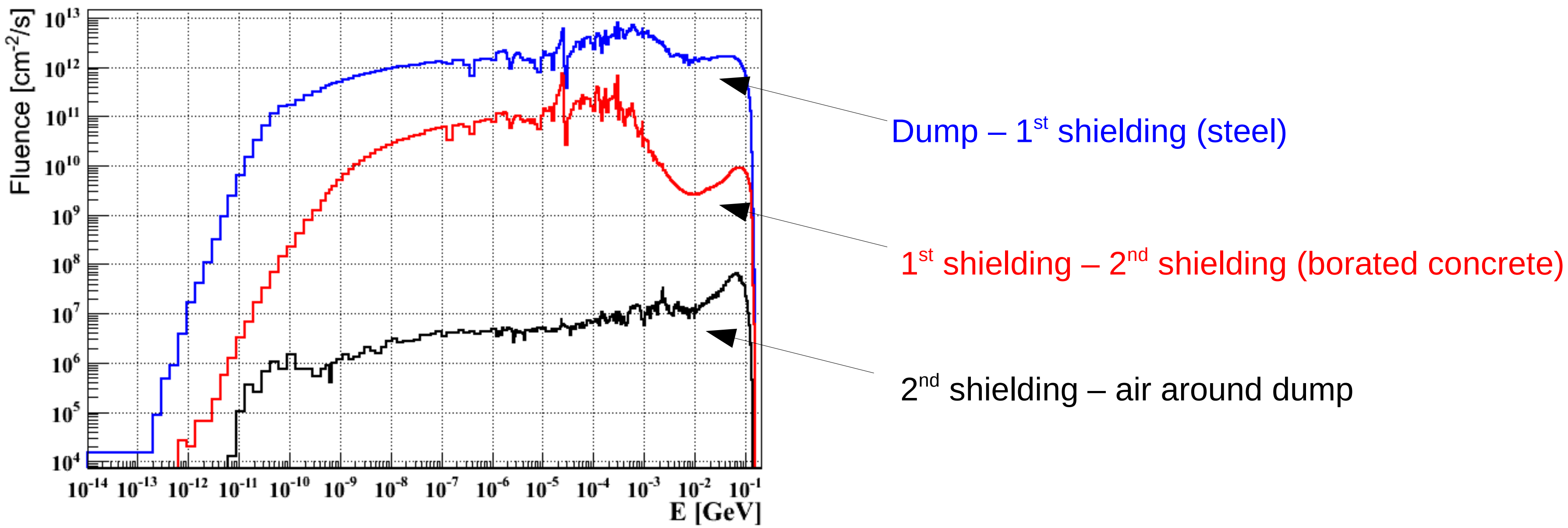
- Fluence maps used to optimize biasing for the calculation of the prompt dose at the Linac2 level (area accessible during Linac4 commissioning)

Neutron spectra

Method:

- 2 USRBDX cards used to score neutron fluence between two different boundaries (dump – 1st shielding, 1st shielding - 2nd shielding, 2nd shielding - air)
- Neutron spectra expressed in lethargy

Results:



- Steel shielding used to reduce high energy neutrons
- Borated concrete used for shielding of neutrons, gammas and other secondaries

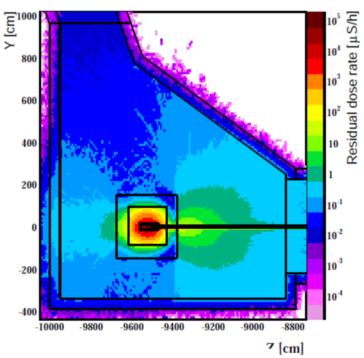
Residual dose rate

Method:

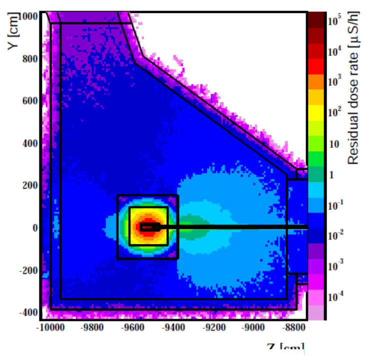
- RADDECAY card activates radioactive decay and sets an optimum threshold for for prompt particles (factor 10). 3 decays (replicas) for each residual nuclide
- 2 IRRPROFI cards describe the irradiation times and corresponding intensities
- USRBIN + DCYSCORE are used for scoring of dose equivalent rate for given cooling time

Results (reliability run, 9 months irradiation):

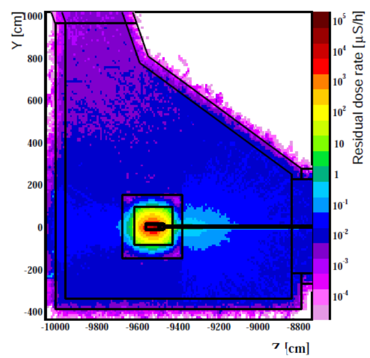
1 hour



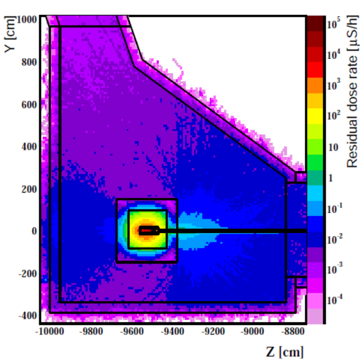
8 hours



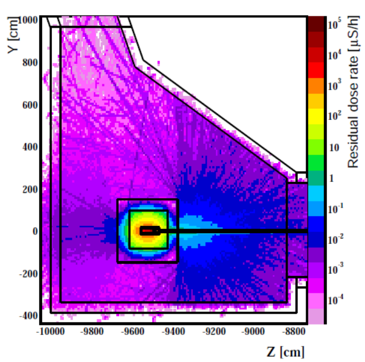
1 day



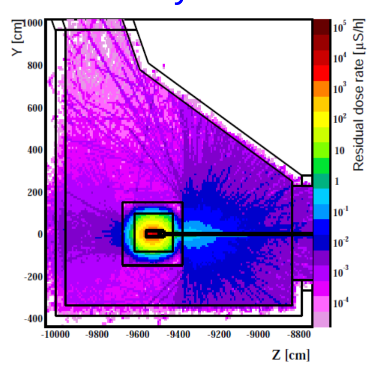
1 week



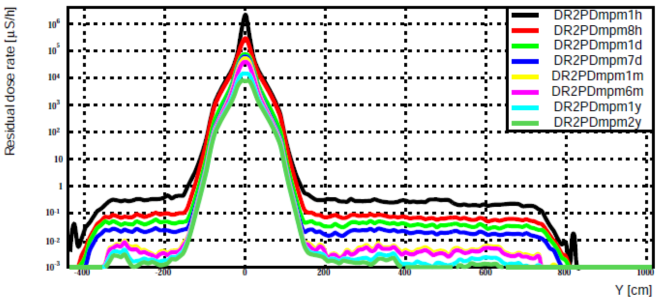
1 month



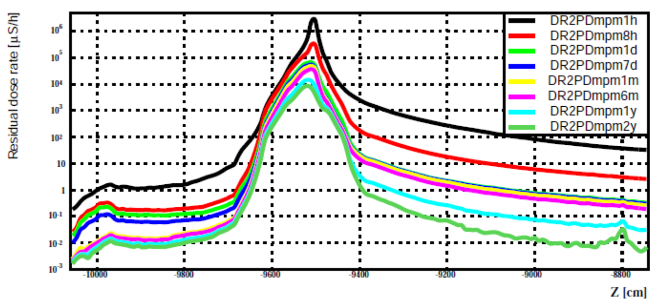
1/2 year



Dose rate along Y axis



Dose rate along Z axis



-> Cavern accessible after short cooling times

Radionuclides inventory

Method:

- RESNUCLE + DCYSCORE cards used to score activity in different regions for several cooling times
- Post processing tool **(J. Vollaire)** for resnucle outputs which generate inventory tables

Results:

Shielding:

Steel

	Half life	Activity	Total	Stat err
^{60}Co	5.3 y	2.58e+10	6.7	0.0
^{59}Fe	44.6 d	6.4e+09	1.7	0.0
^{58}Co	70.8 d	3.43e+10	8.9	0.0
^{57}Co	272.0 d	1.58e+10	4.1	0.0
^{56}Co	77.3 d	5.5e+09	1.4	0.1
^{55}Fe	2.7 y	6.75e+10	17.5	0.0
^{54}Mn	312.5 d	5.22e+10	13.5	0.0
^{51}Cr	27.7 d	1.49e+11	38.7	0.0
^{49}V	338.0 d	1.18e+10	3.1	0.0
^{48}V	16.0 d	4.58e+09	1.2	0.1

Borated concrete

	Half life	Activity	Total	Stat err
^{45}Ca	164.4 d	8.36e+06	4.8	0.3
^{37}Ar	35.1 d	1.31e+08	75.4	0.2
^{35}S	87.5 d	2.75e+06	1.6	1.7
^{32}P	14.2 d	6.06e+06	3.5	0.9
^{22}Na	2.6 y	1.93e+06	1.1	1.0
^{7}Be	53.2 d	1.52e+07	8.7	0.7
^{3}H	12.3 y	4.32e+06	2.5	0.4

- 1 month cooling time
- Only radionuclides which contribute more than 5% to the total activity

Dump:

Carbon

	Half life	Activity	Total	Stat err
^{7}Be	53.2 d	3.73e+11	95.4	0.0
^{3}H	12.3 y	1.8e+10	4.6	0.0

Steel

	Half life	Activity	Total	Stat err
^{58}Co	70.8 d	1.56e+10	11.3	0.0
^{57}Co	272.0 d	8.27e+09	6.0	0.1
^{56}Co	77.3 d	2.99e+09	2.2	0.1
^{55}Fe	2.7 y	2.28e+10	16.6	0.0
^{54}Mn	312.5 d	2.06e+10	14.9	0.0
^{51}Cr	27.7 d	5.7e+10	41.4	0.0
^{49}V	338.0 d	5.02e+09	3.6	0.1
^{48}V	16.0 d	2.06e+09	1.5	0.1

Wall:

Concrete

	Half life	Activity	Total	Stat err
^{55}Fe	2.7 y	1.21e+06	3.4	1.4
^{54}Mn	312.5 d	4.19e+05	1.2	1.7
^{45}Ca	164.4 d	8.66e+06	24.6	0.9
^{37}Ar	35.1 d	2.03e+07	57.5	0.4
^{35}S	87.5 d	4.09e+05	1.2	2.1
^{32}P	14.2 d	4.31e+05	1.2	1.9
^{22}Na	2.6 y	6.01e+05	1.7	0.9
^{7}Be	53.2 d	2.13e+06	6.0	1.0
^{3}H	12.3 y	4.49e+05	1.3	0.5

Radioactive waste

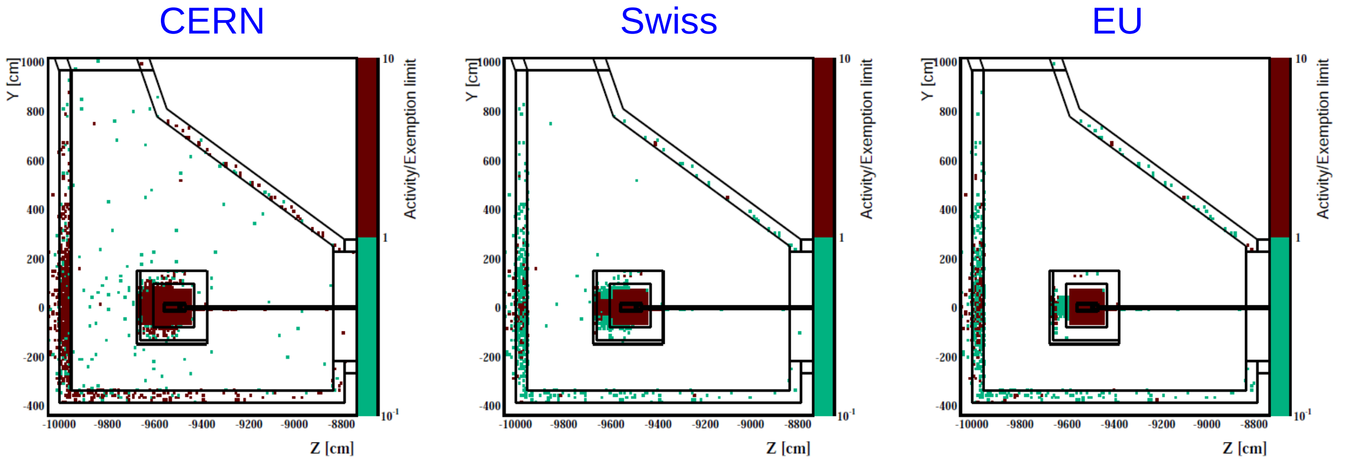
Method:

- USERWEIG card to activate user defined weighting (FLUSCW+, COMSCW+)
- USRBIN + DCYSCORE cards used to score activity (ACTOMASS) for and detector specif name (set of weights)
- Using user defined function **(LEv12.f written by S. Roesler)** which weight the activity "on the fly" with a coefficient related to the "radio toxicity" of the nuclei

Scenario:

- 1 moth of commissioning run + 9 months of reliability run + 20 years of normal Linac4 operation
- 2 years of cooling time

Results:



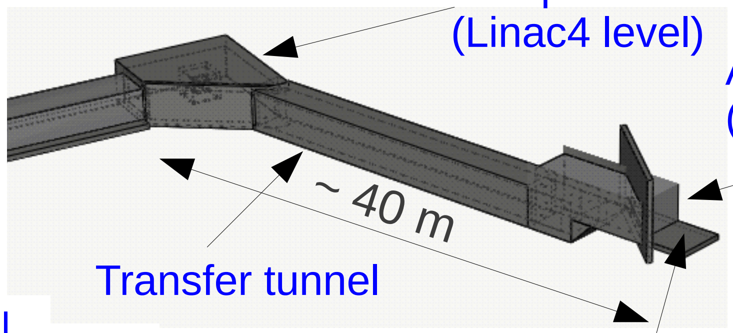
R = Sum(Ai/LEi)

R>1 is a waste

Prompt dose rate

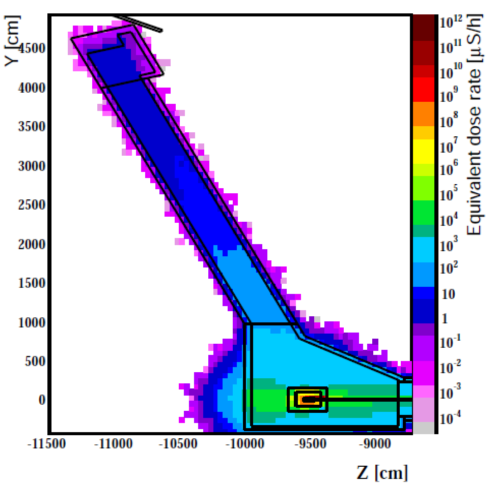
Method:

- EMF-OFF transport electrons and photos switched-off to reduce CPU time of the calculations (results underestimated by about 30% percent?)
- Region importance biasing was used to improve statistic at the Linac2 level
- USRBIN + AUXSCORE cards used for scoring of the ambient dose equivalent rate (using AMB74 conversion coefficients) in a Cartesian mesh

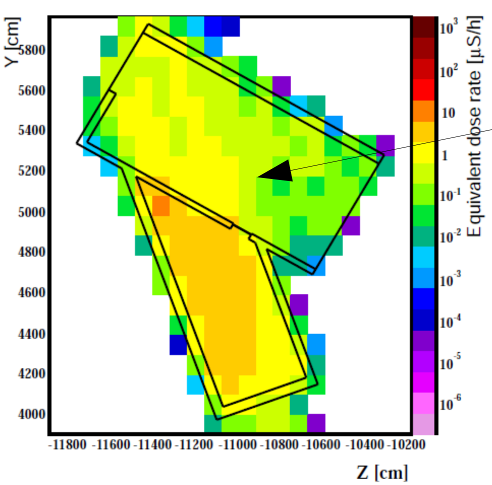


Results:

Linac4 level



Linac2 level



Accessible location during reliability run

Prompt dose at L2 level is several µSv/h

Water activation

Method:

- RESNUCLE card used to calculate the production yield of radiation induced nuclides in water
- Total production yield (for 2.5 l of water inside the dump) used to calculate water activity
- Activity time evolution calculated is calculated offline from the production yield
- Radionuclides considered: H-3, Be-7, Be-10, C-11, C-14, N-13, O-14, O-15

Results:

- Production yield of long life radionuclides:
  - H-3: 5.10E-6 nuclides/primary
  - Be-7: 1.37E-6 nuclides/primary
- Total activity:

	Commissioning run (1 month)	Reability run (9 months)	Commissioning and reability run	After 10 years of operation
A(H-3) [MBq]	1.43	4.79	6.15	26.6
A(Be-7) [MBq]	26.43	30.3	30.8	14.4

N.B. Normal operation: beam power 2.8 kW, occasionally (8hours/week)

- Specific activity can be scaled accordingly (considering the total volume of cooling circuit and its water flow rate)

Airborne radioactivity 1/3

Method:

- USRTRACK card is used to compute track-length spectra for different hadrons (n, p, pi+, pi-) in a wide energy range
- Radionuclides production yields in air is computed by folding the track-length spectra with the production cross section of target nuclide **(done by S. Roesler's routine)**
- Activity is calculate considering the conditions below
- Most important considered nuclides: H-3, Be-7, C-11, N-13, O-15, F-18, Al-28, P-32, Cl-38, Cl-39, Ar-41

Conditions:

- Dump hall + linac4 tunnel air volume: 1329 m3
- 1 year irradiation with a nominal beam intensity of 1.11E+14 protons/s (beam power 2.84 kW)
- Air exchange 1000 m3/h
- 650 s to reach the air release point

Airborne radioactivity 2/3

Results:

- Activity released into atmosphere: 1.62 Gbq
- Residual activity after the beam stop: 0.552 Mbq
- Specific activity: 415 Bq/m3
- Committed effective dose rate: 0.65 nSv/h (< 5 nSv/h)

Conclusions and gained experience

Conclusions:

- The dump shielding consisting of steel and borated concrete fulfills well radio-protection requirements
- Fluka and flair are powerful tools for various radio-protection calculations

What I have learnt when using fluka:

- Effective fluka calculations depends on an effective input
- One task can be done by several different ways (usually if you ask different people)
- No need to have always large numbers of primaries, but find out the optimal biasing, binning, and physics setting – or always think how much CPU it will take

Acknowledgment

Thank to all FLUKA, FLAIR, SimpleGeo, and ROOT developers for using their powerful software

Special thank to Joachim Vollaire for giving me many useful advises and providing me his own post processing routines