CERN

Radiological characterization of radioactive magnets at CERN

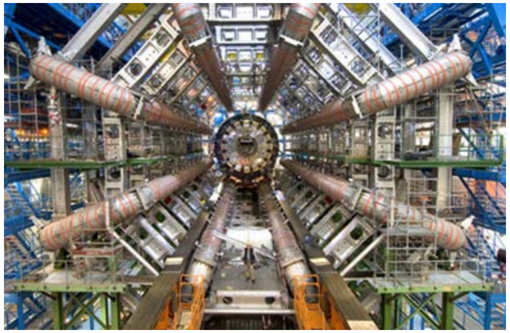
T. Frosio, M. Magistris, N. Menaa, Y. Pira, M. Rimlinger, S. Roesler, C. Theis, B. Zaffora

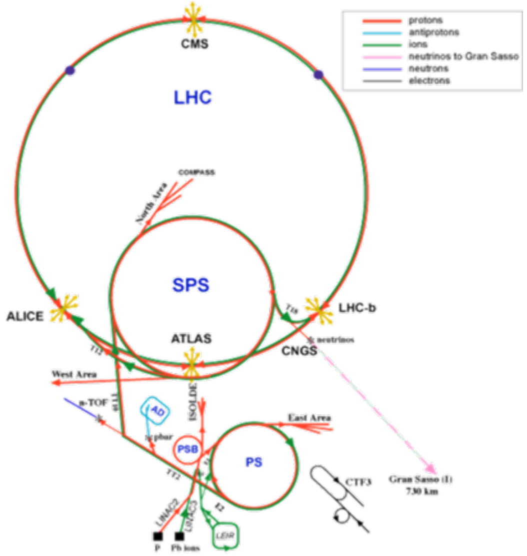
Outline

- **Introduction**
  - The CERN accelerator complex
  - Radioactive waste at CERN
  - Magnets, general description
  - Acceptance criteria in a final repository
- Radiological characterization
  - Standard methodology at CERN
  - New methodology for magnets
  - Radionuclide inventory
  - Conversion functions
  - Operational procedure
  - Validation
- Conclusions

Introduction
The CERN accelerator complex

- Founded in 1954, the CERN laboratory sits astride the Franco-Swiss border near Geneva.
- The accelerator complex is a succession of machines that accelerate particles to increasingly higher energies. In the LHC – the last element in this chain – particle beams are accelerated up to 6.5 TeV per beam.





Introduction
Radioactive waste at CERN

- In high-energy particle accelerators, beam particles can interact with gas molecules and accelerator components, and lead to material activation.
- The radiological characterization of radioactive waste is a requirement for its disposal in the national final repositories.
- This presentation will focus on the characterization of very-low-level waste (VLLW), including large electric magnets.

All calculations were performed with the analytical code ActiWiz (*see presentation by Chris Theis in the 4th ARIA Workshop*)

Introduction
Magnets, general description

- There are over 100 magnets which are stored at CERN and require radiological characterization
- These magnets are made of copper coils, an iron yoke and a supporting steel structure
- The mass can vary from 1 to 30 tons, and the length can reach 6 metres

Example of magnets which are temporarily stored at CERN

- *A project was launched in 2017 to characterize and eliminate magnets towards the final repository for waste with Very-Low-Level activity (VLLW) in France.*

Introduction
Acceptance criteria for VLLW (very-low-level waste)

- The acceptance criteria for the disposal of VLLW in the French repository of Cires (ANDRA) are:
  - The contamination level on accessible surfaces must be below acceptance limits
  - The so-called IRAS* factor ($\sum_i {}^{a_i}/_{LIM_i}$) of a waste package must be < 10.
  - The average IRAS factor of a batch of waste ($\frac{\sum_j M_j * IRAS_j}{M_{batch}}$) must be < 1.
- These acceptance criteria are set by the safety requirements of the final repository.

Example of waste package with pieces of copper

	Activity limits (Bq/g)	Declaration limits (Bq/g)		Activity limits (Bq/g)	Declaration limits (Bq/g)
H-3	1000	1	**Ti-44**	10	0.1
C-14	1000	0.01	**Mn-54**	10	0.1
Na-22	10	0.1	**Fe-55**	1000	10
Cl-36	1000	0.01	**Co-60**	10	0.1
Ar-39	1000	10	**Ni-63**	1000	10
Ca-41	1000	0.01	**Ag-108m**	10	2.5E-4

* IRAS = Indicateur Radiologique d'Acceptation en Stockage

Outline

- Introduction
  - The CERN accelerator complex
  - Radioactive waste at CERN
  - Magnets, general description
  - Acceptance criteria in a final repository
- **Radiological characterization**
  - Standard methodology at CERN
  - New methodology for magnets
  - Radionuclide inventory
  - Conversion functions
  - Operational procedure
  - Validation
- Conclusions

Radiological characterization
Standard methodology at CERN

In the general case, the characterization of Very-Low-Level waste at CERN is performed as follows:

1. Identify a batch of homogeneous waste, e.g. 100 tons of cables
2. Use ActiWiz to identify the radionuclide inventory, i.e. radionuclides which can have an activity above the declaration limit defined by ANDRA
3. Evaluate the specific activity depending on the nuclide:
   - Easy-to-measure nuclides: in-situ gamma spectrometry or dose-rate measurements on the waste packages
   - Difficult-to-measure nuclides:
     - Sampling followed by gamma-spectrometry and radiochemical analysis
     - Use of experimental scaling factors (activity ratios) or mean activity
   - Impossible-to-measure nuclides:
     - Use of analytical scaling factors
4. Calculate the IRAS factor for each waste package

Radiological characterization
Why do we need a new methodology for magnets?

The characterization of CERN radioactive magnets is particularly challenging.

- They are > 1 m in length and > 1 ton in mass
  - In-situ gamma spectrometry is difficult (logistical reasons) and time consuming (several measurement points needed)
- They are made of different metals (e.g. cast iron and copper) in different proportions.
  - Difficult to define one representative radionuclide inventory
- They are often of unknown radiological history.
  - No information on activation scenarios (beam losses, energies, irradiation pattern, etc.)
- They present heterogeneous activity distribution.
  - The activity distribution will affect the modelling in gamma spectrometry, as well as the representativeness of samples
- The may require handling in a dedicated workshop
  - A dedicated workshop may not be adequate for sampling, as it would generate radioactive dust

A new method is needed, which would not require in-situ gamma spectrometry or sampling.

Radiological characterization
New methodology for magnets

The radiological characterization of magnets at CERN is performed as follows:

- An initial scientific study with ActiWiz and FLUKA:
  - Expected radionuclide inventory
  - Conversion functions (to convert dose-rate to activity)
- A fast and simple characterization procedure:
  - Dose-rate map of the magnet
  - Application of conversion functions

The scientific study can be applied to all VLLW electric magnets which are currently temporarily stored at CERN.

The characterization procedure does not require gamma spectrometry, nor sampling.

Radiological characterization
Radionuclide inventory

- The radionuclide inventory was defined by studying > 300 possible activation scenarios with ActiWiz, including:
  - The materials copper (for the magnet coil), iron (magnet yoke) and steel (supporting structure)
  - Different irradiation and waiting times (from 3 to 40 years)
  - Proton beam losses with energy 1.4 GeV to 7 TeV

	Fe	Mn	Cu	C	P	N	Co	Sn	S
Iron_ARMCO	99.887	0.06	0.03	0.01	0.005	0.005	0.005	0.005	0.003

Most relevant nuclides   Co-60   Ag-108m

	C	Cr	Co	Fe	Mn	Ni	P	Si	S
Steel_304L	0.03	18.5	0.1	67.0825	2.0	11.25	0.0225	1.0	0.015

Co-60   H-3 Mn-54 Fe-55   Cl-36, Ar-39 Co-57

	Cu	Ag	S	Bi	Pb	O	Cd	Hg	Zn
Copper_OFE	99.94	0.05	0.0018	0.001	0.001	0.0005	0.0001	0.0001	0.0001

Most relevant nuclides   Na-22

Radiological characterization
Radionuclide inventory

Tritium

- Produced via spallation in iron, stainless steel and copper
- Can end up in a chemically bound form, or in the form of gas (cannot be predicted by FLUKA or ActiWiz).
- If in the form of gas, by the time the magnets are eliminated the H-3 would have diffused out almost completely.
- Results for shredded metallic waste campaigns used for verification:

		Scaling factors		
Campaign	**Samples**	**Radionuclides (DTM/KN)**	**Analytical**	**Experimental**
C002	32	H-3/Co-60	1.4	1.7
C004 (part A)	20	H-3/Ti-44	84	63
C004 (part B)	7	H-3/Ti-44	84	71

- The good agreement indicates that the predictions made with ActiWiz do not overestimate the presence of H-3 in the waste.

Radiological characterization
Conversion functions

Goal:

Definition of conservative dose rate – to – specific activity conversion functions for entire magnets based on minimal input knowledge

Recipe:

1. ActiWiz calculation of fingerprints* for different irradiation scenarios (energy, location, irradiation time, cooling time) and materials
2. Calculation of average fingerprint for each material over different scenarios
3. Calculation of average fingerprint for entire magnet weighted with mass fractions of material

$$F_i = \sum_{j=1}^{3} m_j \times \frac{f_{i,j}}{\sum_l f_{l,j}}$$

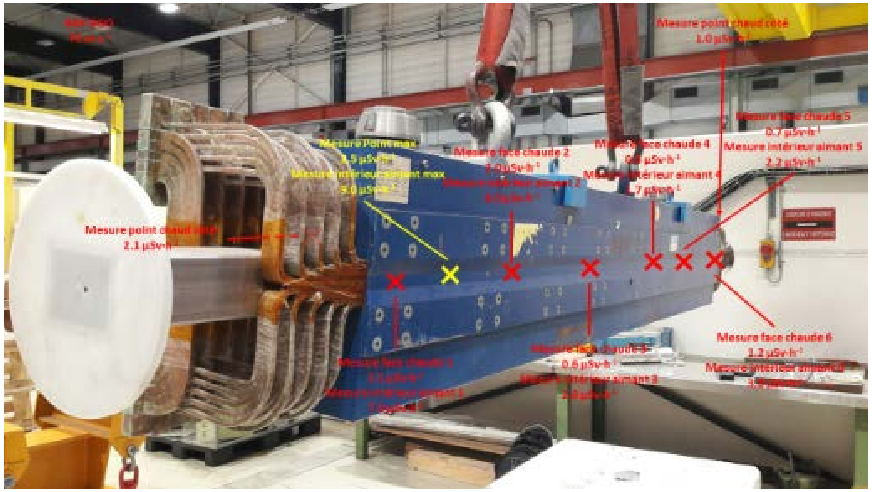
4. Evaluation of activity of a radionuclide from the dose-rate measurements with a conversion function, that is established on the basis of the dominant gamma emitters (Ti-44, Mn-54 and Co-60)

$$A_i = CF_i \times DR = \frac{F_i \times DR}{F_{Ti-44}/cf_{Ti-44} + F_{Mn-54}/cf_{Mn-54} + F_{Co-60}/cf_{Co-60}}$$

***fingerprint** = list of radionuclides with their activity expressed as percentage of the total activity $f=(f_1,f_2,f_3,\dots)$

Radiological characterization
Operational procedure

- The dose-rate is measured in contact with well-defined points of the magnet, and an average dose-rate is calculated
- The specific activity of each radionuclide is evaluated via a conversion function, which is multiplied by the average dose-rate



Dose-rate cartography of a magnet to be characterized

	Global conversion factors (Bq/g)/(µSv/h)		
Waiting time	3 to 10 years	10-20 years	20-40 years
H-3	21.6	33.3	32.7
C-14	0.003	0.01	0.02
Na-22	0.08	0.02	0.001
Cl-36	4.50E-04	0.001	0.003
Ar-39	0.5	1.2	2.7
Ca-41	0.001	0.002	0.004
Ti-44	0.4	0.9	1.8
Mn-54	0.6	0.002	n.a.
Fe-55	48.6	14.1	0.7
Co-60	1.3	1	0.3
Ni-63	1.3	3.1	6.3
Ag-108m	0.003	8.20E-03	0.02

Radiological characterization
Validation with gamma spectrometry

- The methodology was validated by selecting 2 magnets, and counting them by gamma spectroscopy.
- The activity values are compared to the ones computed with the conversion function.

"Blue magnet" selected for validation

"Orange magnet" selected for validation

Validation
Comparison with gamma spectrometry

- The characterization method of conversion function agrees well with in-situ gamma spectrometry.
- The transfer functions activity results are consistently conservative.
- The major source of conservativeness comes from the dose-rate map, which is performed on the most radioactive side of the magnet.

Blue magnet	Dose-Rate uSv/h	Na-22 Bq/g	Sc<Ti-44 Bq/g	Co-60 Bq/g
Conversion function (CF)	10.3	0.2	9.3	10
Gamma spectrometry (GS)		0.1	6.2	9.2
Ratio CF/GS	-	2.0	1.5	1.1

Orange magnet	Dose-Rate uSv/h	Na-22 Bq/g	Sc<Ti-44 Bq/g	Co-60 Bq/g
Conversion function (CF)	3.93	0.08	3.5	3.9
Gamma spectrometry (GS)		0.04	2.2	3.4
Ratio CF/GS	-	2.0	1.6	1.1

One of a series of in-situ gamma-spectrometry measurements performed on the “blue magnet”

Outline

- Introduction
  - The CERN accelerator complex
  - Radioactive waste at CERN
  - Magnets, general description
  - Acceptance criteria in a final repository
- Radiological characterization
  - Standard methodology at CERN
  - New methodology for magnets
  - Radionuclide inventory
  - Conversion functions
  - Operational procedure
  - Validation
- **Conclusions**

Conclusions

- Thanks to extensive calculations with ActiWiz and Fluka, we defined representative radionuclide inventories and conversion factors which apply to electric magnets:
  - From a variety of proton machines at CERN
  - With different radiological history
  - With a mixture of different metals
- A simple dose-rate map – and the application of conversion functions – leads to a full radionuclide inventory in good agreement with results from gamma spectrometry.
- It is important to involve the national Authorities at an early stage in the conception of a new characterization methodology
- Quality assurance is fundamental for radiological characterization and should include detailed work instructions and regular quality controls

CERN