Workshop on Accelerator Radiation Induced Activation
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Knoxville, Tennessee, USA
Hosted by the Spallation Neutron Source, Oak Ridge National Laboratory, USA

The Radiological Workstation - an Efficient Tool for In-Situ Characterization of Potentially Radioactive Material

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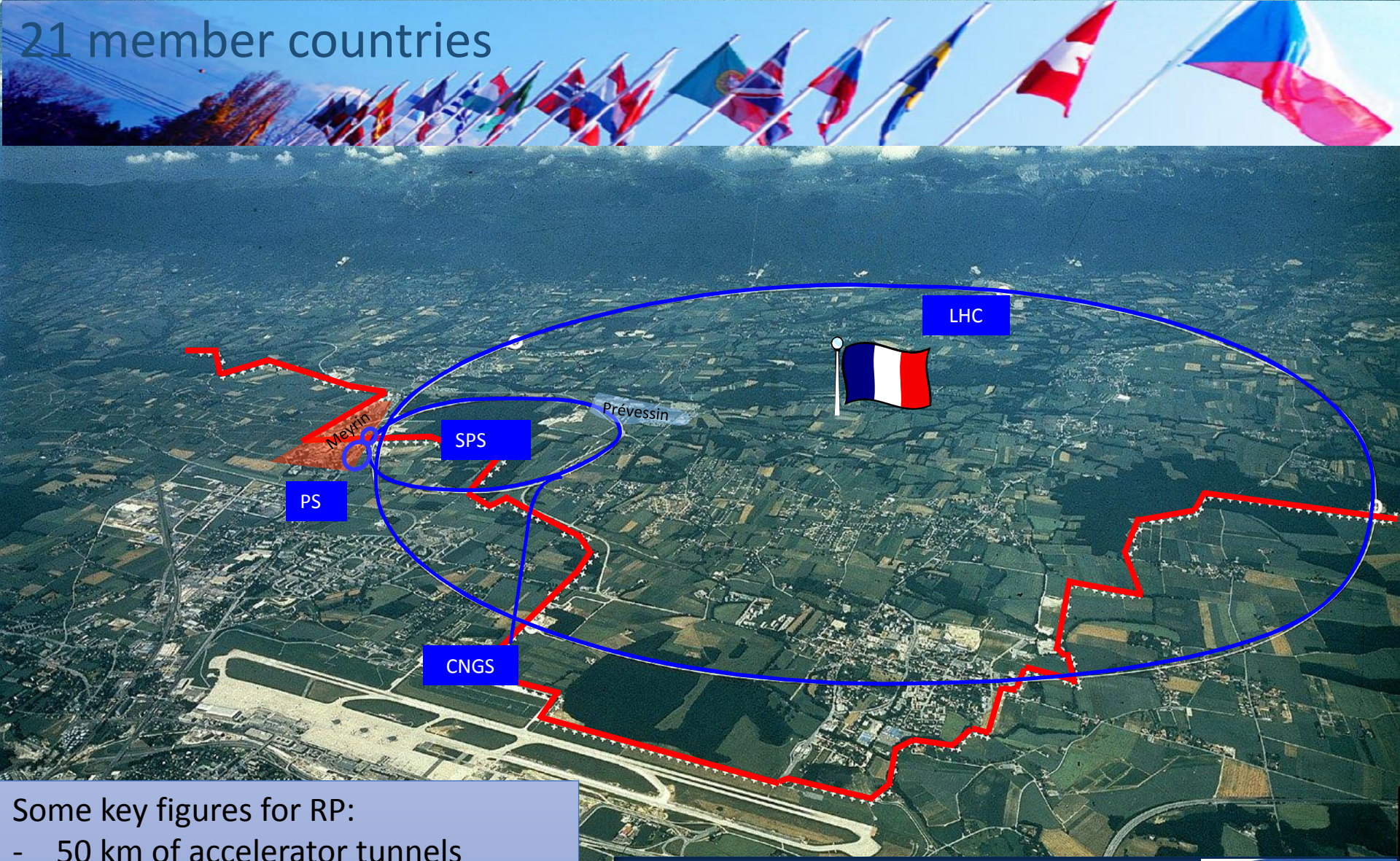
21 member countries



Some key figures for RP:

- 50 km of accelerator tunnels
- 50 - 60 access points
- 160 experiments
- 9300 occupationally radiation-exposed persons

~ 2400 employees
~ 790 associates
~ 3500 external workers
> 11000 users from 100 countries

theguardian
Winner of the Pulitzer prize

Large Hadron Collider

Sunday 5 April 2015 20.48 BST

Cern restarts Large Hadron Collider with mission to make scientific history

Physicists hope particle accelerator will explain dark matter, gravity and antimatter as it completes its test run following an upgrade

Ian Sample Science editor

@iansample

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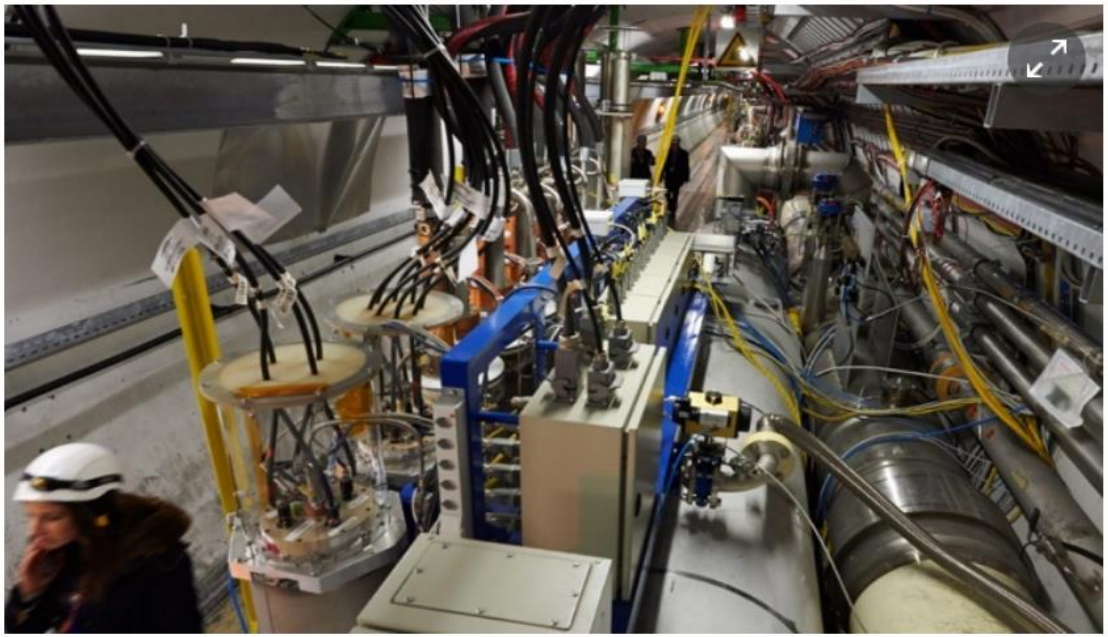


The Large Hadron Collider at Cern in 2013. Engineers have spent the past two years reinforcing its connections and building in safety devices to prevent a short circuit. Photograph: Adam Warzawa/EPA

LS1

LS1: Long shut down during the last two years

http://www.theguardian.com/science/2015/apr/05/cern-restarts-large-hadron-collider-with-mission-to-make-scientific-history

Why to *Increase* the Efficiency ?

Increasing Energy, Increasing Luminosity☺
Increasing size of Accelerators & Experiments.
Increasing quantities of potentially radioactive material☹

Example LS1	
# RP controls	39395
Total mass	3373 t
Potentially radioactive	2618 t
Potentially radioactive waste	722 t

LS1

Nature	Volume (m3)	Masse (T)
Wood	5,7	1,4
Metallic waste	50,5	28,3
Ion-exchange resins	1,5	1,0
Filters	68,9	3,8
Motors and Pumps	8,8	3,3
Concrete	41,1	33,7
lighting	0,8	0,5
ceramic	0,5	0,1
connectors	0,7	0,2
Wires & cables	30,6	13,7
Lead	0,6	1,0
Aluminium	6,2	2,1
Copper	3,9	5,8
Insulation	80,6	12,6
Stainless Steel	1,4	0,9
Liquids	82,6	72,2
Combustible	65,9	4,9
Iron	189,2	71,1
Dust	0,5	1,2
Valves	1,5	0,2
Containing Asbestos	186,5	39,0
Others	6,0	0,9
TOTAL	834,0 m^3	297,8 t

40% of the LS1 waste is a potential candidate for clearance

Why to discuss the procedures for characterization at CERN now?

- In the near future, the SWISS ordinance, which defines the limits for clearance at CERN, will become more restrictive.
- The clearance procedures at CERN will have to be adapted accordingly.

The Goal:

In order to accomplish the new regulations, a project was launched with the title: "Material characterization for operational aspects".

Timeline:

2-3 years

When is a Material Non-Radioactive?

1. The contamination of its surface below the CS-limit.

and

2. The actual dose rate after background suppression is below 0.1 µSv/h @ 10 cm distance.

and

3. The specific or absolute activity of a radio-nuclide is below the exemption limit LE.

Real objects contain normally a large number of different radio-nuclides:

$$S = \sum_i \frac{a_i}{LE_i} < 1$$

ORAP Switzerland

a_i: activity of the nuclide i
LE_i: exemption limits as defined by the ordinance.
S: Summation Rule

Example for Clearance

- Piece of Steel 316 L Size: 8x4x4 cm^3.
  Weight 1kg.
- Installed at LHC adjacent to the magnets.
- Irradiation Time: 1year.
- Cooling Time: 1 week.
- The count rate @ 1 cm is 100 cps.

Steel 316 L

CARBON	0.03	NICKEL	12.5
CHROMIUM	17.25	NITROGEN	0.05
COBALT	0.1	PHOSPHO	0.015
IRON	64.8	SILICON	1
MANGANES	2	SULFUR	0.005
MOLYBDEN	2.25		

Irradiated Object

FHZ 512 BGO

Question : Is the sample radioactive or not?

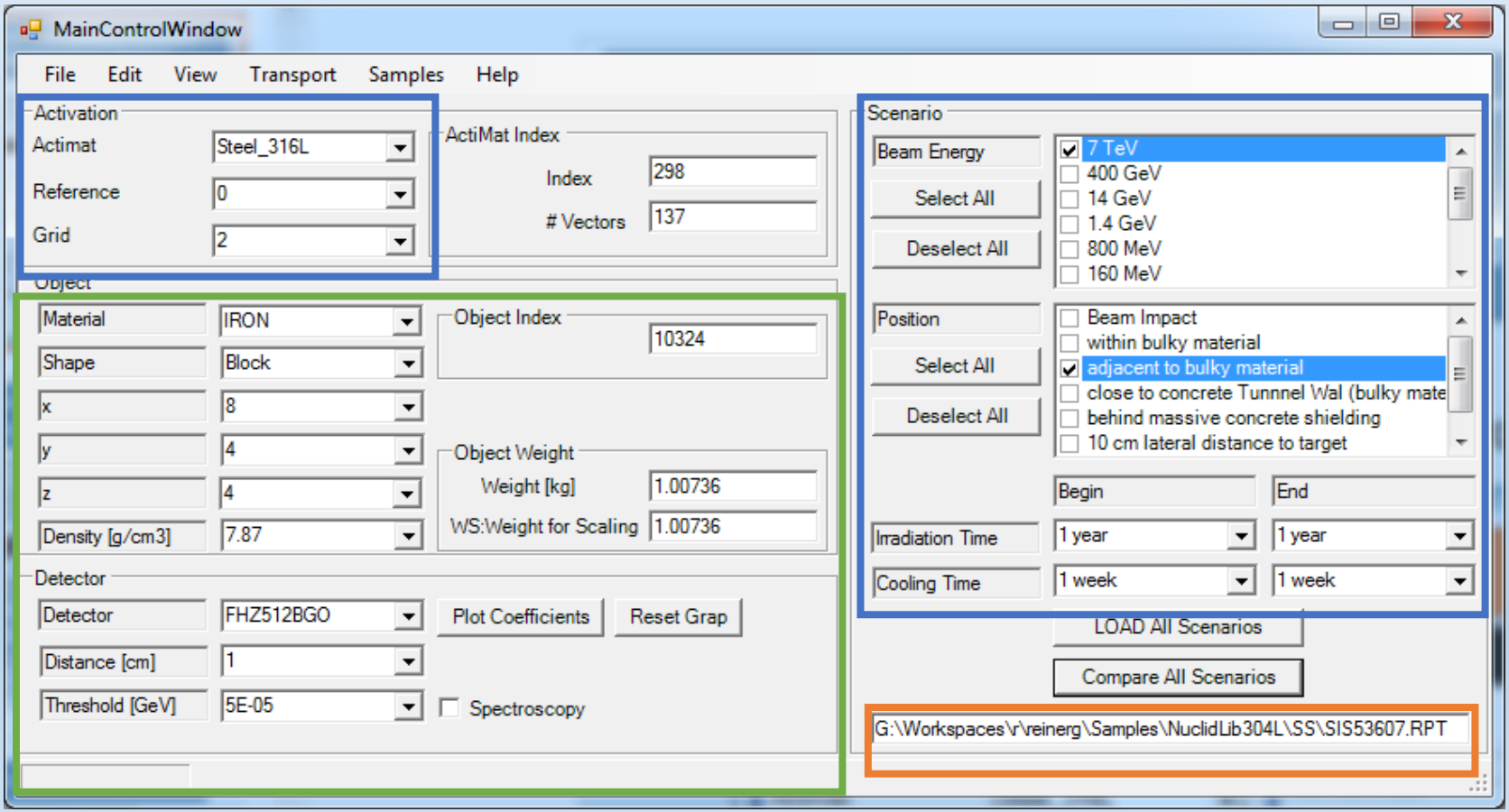
How can we interpret our measurement? ➔Radiological Workstation (RAW)

Software combines:

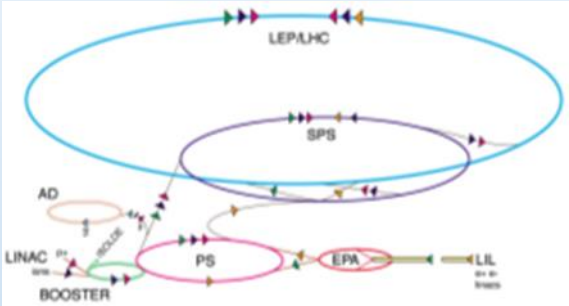
- Measurement results (from either rate or spectroscopy measurements).
- Radionuclide information provided by ActiWiz (software developed in RP).

> 10000 measurement setups

130 × 5460 nuclide inventories (Actiwiz)



Irradiation Scenarios of Actiwiz



160 MeV (Linac4),
1.4 GeV (Booster),
14 GeV (PS),
400 GeV(SPS),
7 TeV (LHC)

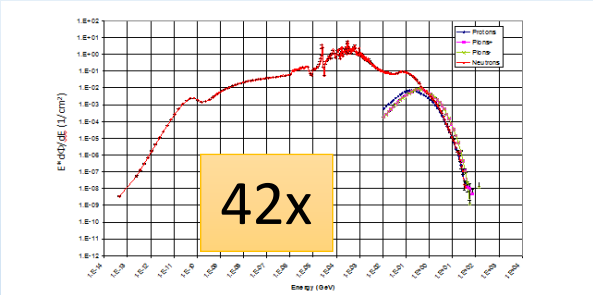
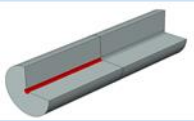
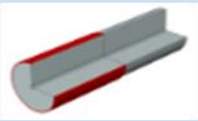
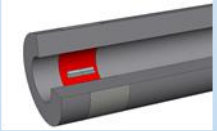
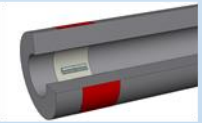
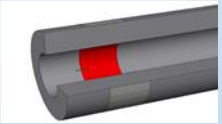


Figure 5: Particle fluence per beam particle scored inside the bulky material which surrounds the beam impact area.





Beam Impact; within bulky material;
adjacent to bulky material; close to the concrete tunnel wall;
bulky material; behind massive concrete shielding;
10 cm lateral distance to target;
close to the concrete tunnel-wall beam on target;

Simplified model!

Predefined set of Irradiation times.
Predefined set of Cooling Times.

5460 Predefined Irradiation Scenarios

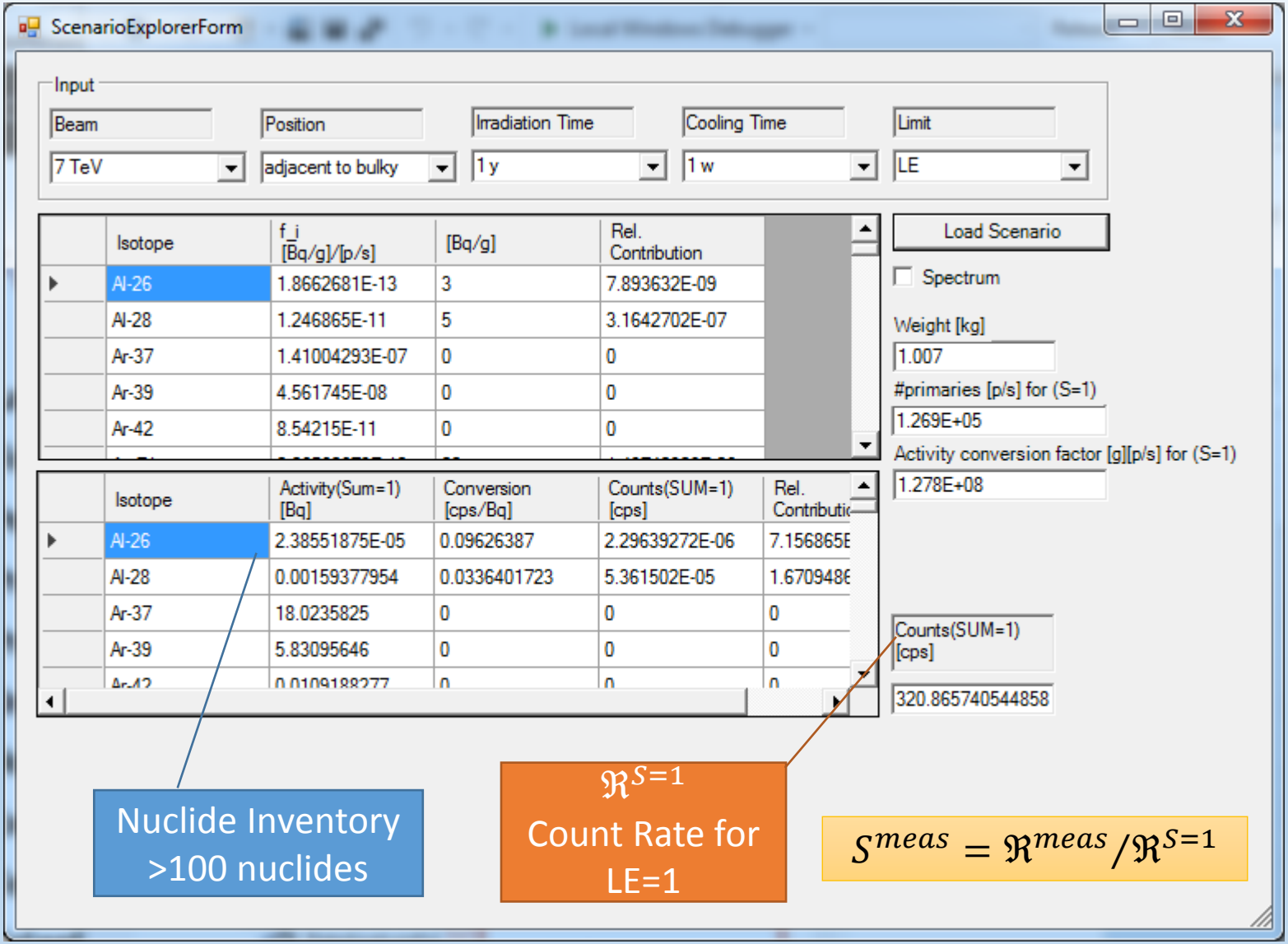
Accelerator Index: a		*Position Index: p*		*Irradiation time b*		*cooling time c*	
0	*7 TeV*	*0*	*beam impact*	*0*	*1 w*	*0*	*1 d*
1	*400 GeV*	*1*	*bulky material*	*1*	*1 m*	*1*	*1 w*
2	*14 GeV*	*2*	*adjacent to bulky*	*2*	*2 m*	*2*	*2 w*
3	*1.4 GeV*	*3*	*close to the concrete tunnel*	*3*	*4 m*	*3*	*1 m*
4	*800 MeV*	*4*	*Behind massive concrete shielding*	*4*	*8 m*	*4*	*2 m*
5	*160 MeV*	*5*	*10 cm lateral distance to target*	*5*	*1 y*	*5*	*4 m*
		6	*close to the concrete tunnel-wall*	*6*	*2 y*	*6*	*8 m*
				7	*5 y*	*7*	*1 y*
				8	*10 y*	*8*	*2 y*
				9	*20 y*	*9*	*5 y*
						10	*10 y*
						11	*20 y*
						12	*40 y*

- $T_{a,p,b,c}^{elem,compound} = \{(N_1, f_1), (N_2, f_2) \ldots \ldots . (N_N, f_N)\}$ [3]
- f_i: specific activity of the nuclide N_i per beam loss rate R. f_i is a prediction of the simulation and has the units [Bq/g]/(p/s)] .
- $a_i = f_i \cdot R$ [2]

$T_{a,p,b,c}^{elem,compound}$ are stored in an activation data base for very fast analysis.

69 chemical elements; 51 compounds; user defined compounds .

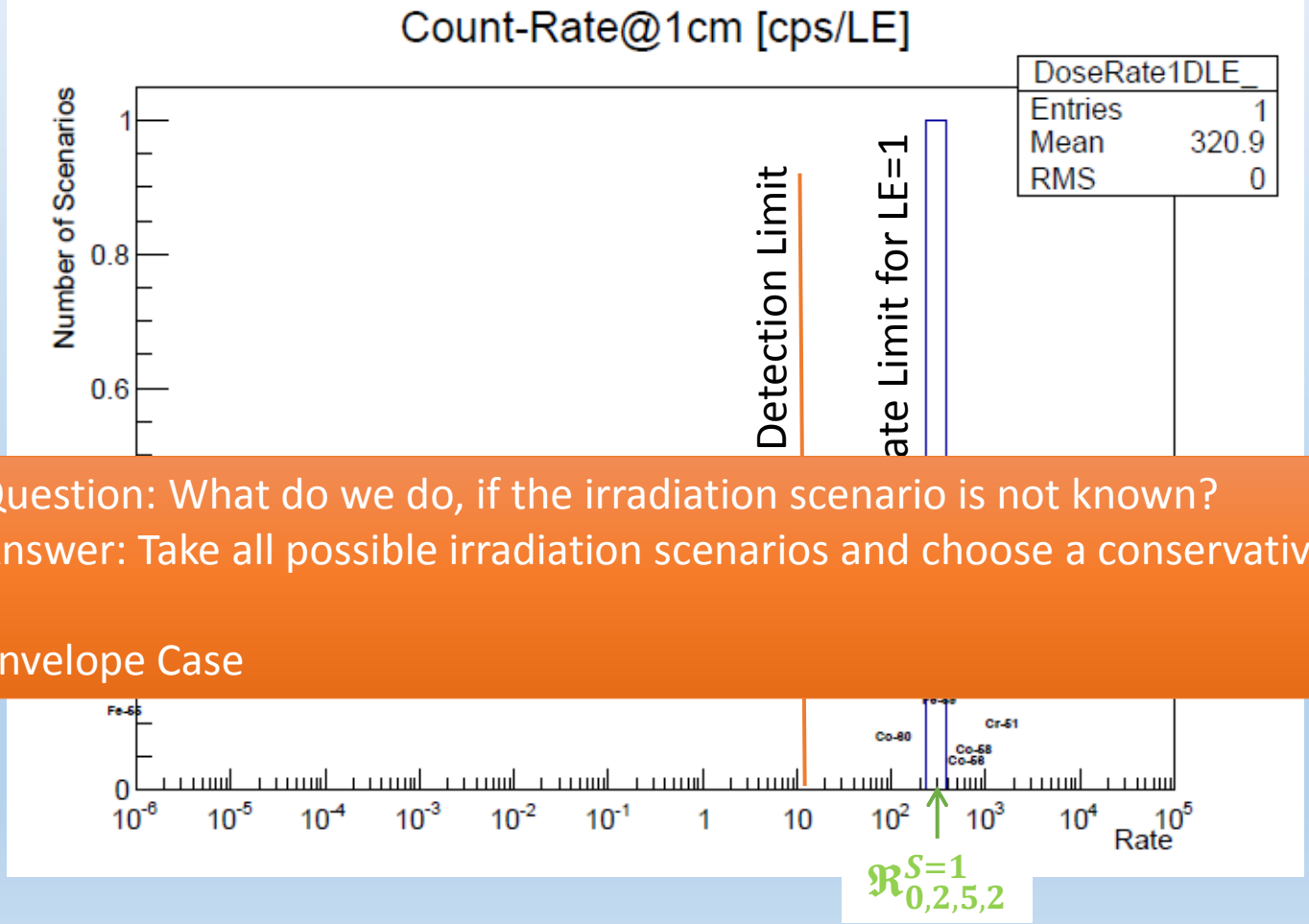
$$\Re^{S=1} = \sum_{i=1}^{N} a_i^{S=1} \sum_{j=1}^{M} Br_{i,j}\,\varepsilon(E_{i,j})\ [7],\ \text{with } a_i^{S=1} = \frac{f_i}{\sum_{i=1}^{n} \frac{f_i}{LE_i}}\ [6]$$



Result produced by RAW

The irradiation scenario from the example

Present Limits LE.



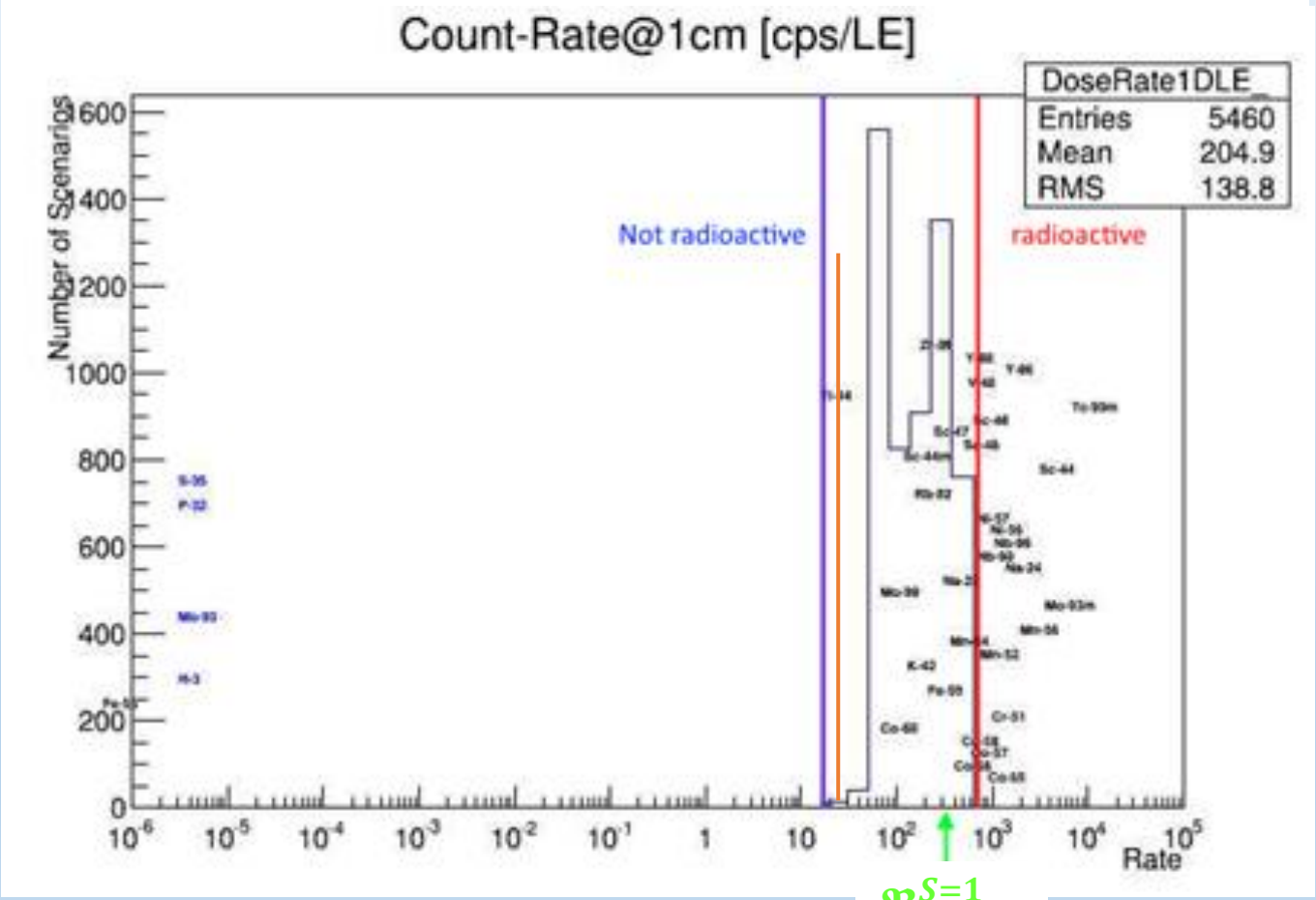
Question: What do we do, if the irradiation scenario is not known?
Answer: Take all possible irradiation scenarios and choose a conservative limit.

Envelope Case

Result by RAW

Envelope of 5460 irradiation scenarios.

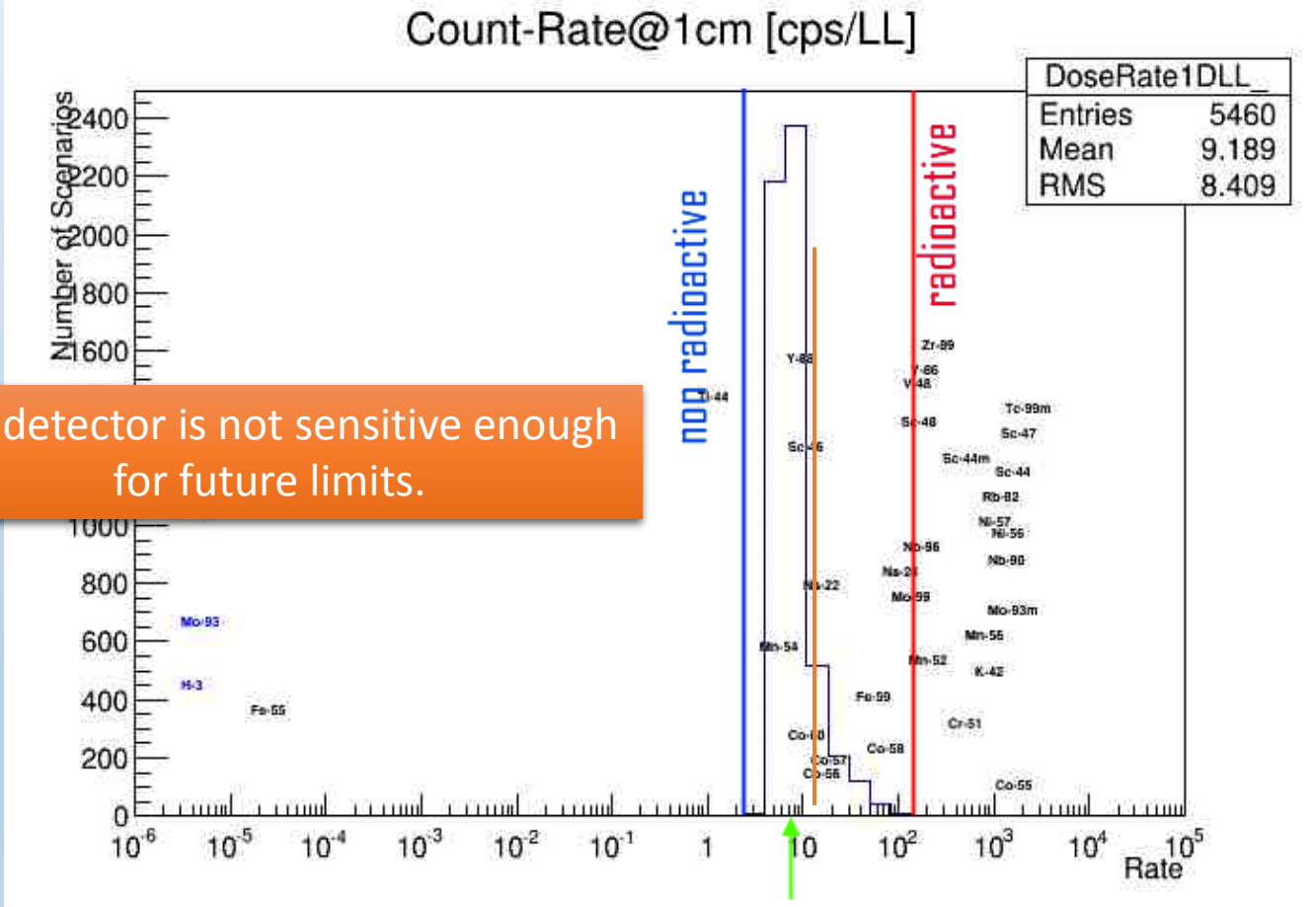
Present Limits. Steel 316 L



Result by RAW

Envelope of 5460 irradiation scenarios.

Future Limits. Steel 316 L



The detector is not sensitive enough for future limits.

$\Re^{S=1}_{0,2,5,2}$

Result by RAW

Current Situation

- Dose rate measurement are sufficient for many situations.

- For doubtful cases the equipment has to be analyzed in the gamma spectroscopy lab.

- For very doubtful cases even further analysis concerning α and β activation has to be considered.

- The new more stringent exemption limits will strongly increase the need of laboratory analysis. This will result in:
  1. Large number of samples, which cannot be handled anymore with current equipment.
  2. very long waiting times for equipment owners.

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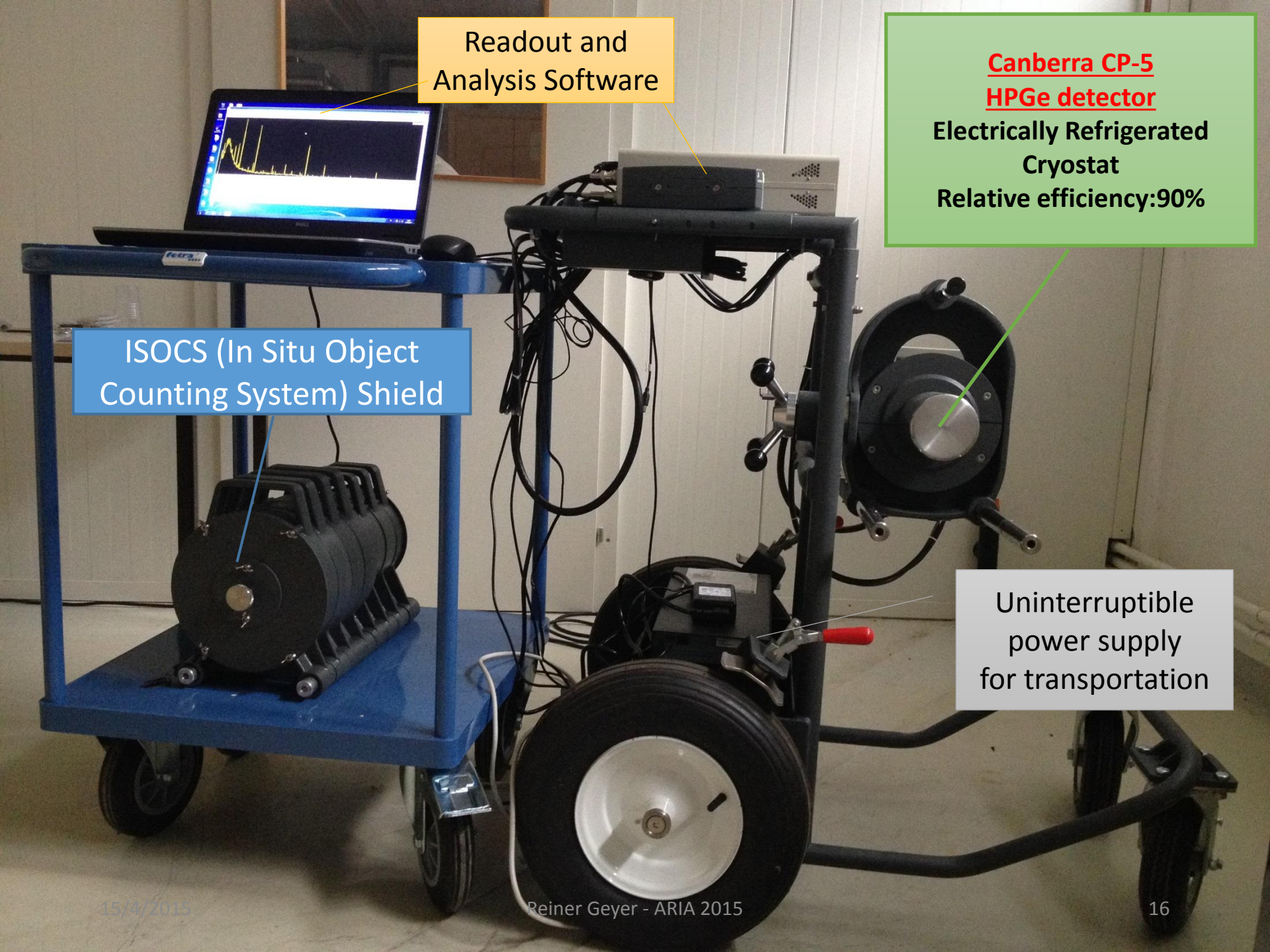
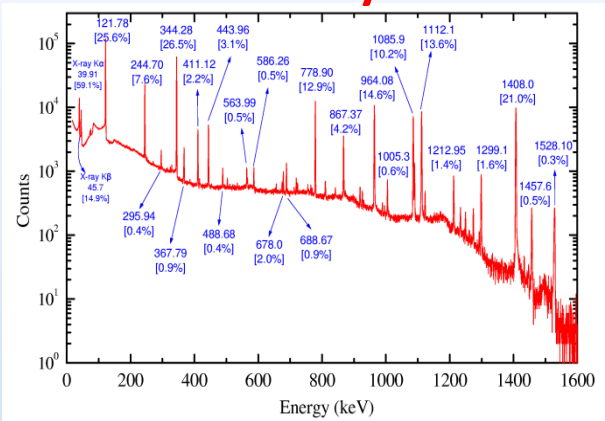
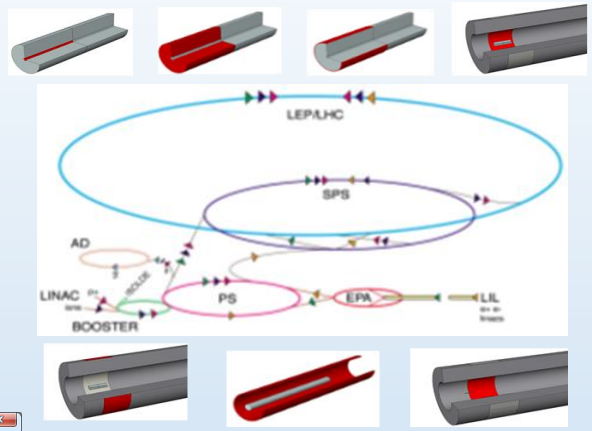

Readout and Analysis Software
Canberra CP-5
HPGe detector
Electrically Refrigerated Cryostat
Relative efficiency:90%
ISOCS (In Situ Object Counting System) Shield
Uninterruptible power supply for transportation

Sample with known or unknown irradiation history.

ActiWiz

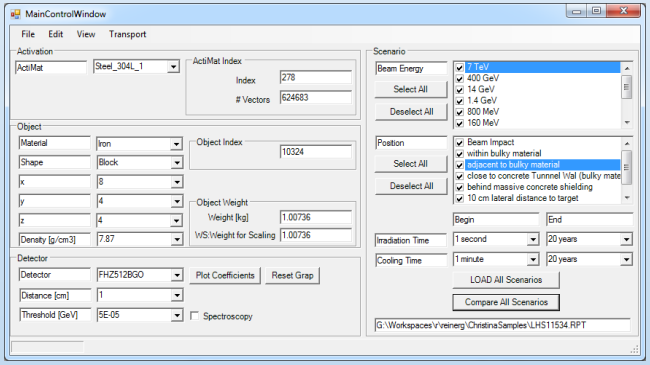


Measured γ lines



130 × 5460 complete nuclide inventories (α + β + γ)

RAW



Integrated system allowing for a full radionuclide analysis by combining gamma spectroscopy with simulation results.

RAW should help to:

- to complement the measured nuclide content.
- To identify the best suited irradiation scenarios.
- to provide classifications as “radioactive” or “non-radioactive”.

Comparison of samples with spectroscopy measurements

- f_i: specific activation of the nuclide i per beam loss rate [Bq/g/(p/s)]. f_i is a prediction of the simulation .
- a_i^{meas}: measured specific activity [Bq/g].
- R_i: beam loss rate (unit [p/s]) required in the simulation to obtain the activity a_i^{meas}. R_i can be estimated by using the relation: $R_i = a_i^{meas}/f_i$.
- $\overline{R} = \frac{\sum_{i=0}^{N} w_i R_i}{\sum_{i=0}^{N} w_i}$: error weighted mean of loss rate averaged over N radio nuclides.
- $a_i^{calc} = f_i \cdot \bar{R}$: estimate for the specific activation for the nuclide N_i from simulation.
- $a_i^{mixed} = \begin{cases} a_i^{meas} \; for \; a_i^{meas} > 0 \\ a_i^{calc} for \; a_i^{meas} = 0 \end{cases}$
- $\chi^2 = \sum_{i=1}^{N} \chi_i^2 = \sum_{i=1}^{N} \frac{\left(a_i^{meas} - a_i^{calc}\right)^2}{\sigma_i^{meas^2} + \sigma_i^{calc^2}}$ agreement between measurement and simulation in terms of χ^2.
- $\mathcal{R}atio_i = a_i^{calc}/a_i^{meas}$.

Summation Rules

- $S = \sum_{i=1}^{n} \frac{a_i}{LE_i}$: sum rule as defined by the ordinance.
- $S_{meas} = \sum_{i=1}^{n} \frac{a_i^{meas}}{LE_i}$: sum rule calculated by the measured nuclides. S_{meas}<=S.
- $S_{mixed} = \sum_{i=1}^{n} \frac{a_i^{mixed}}{LE_i}$: for nuclides which could not be measured, the simulation result is used.

Our clearance example to be identified with spectroscopy

Technical Note

CERN-DGS-2012-004-REPORTS-TN

Placement of material samples outside LHC interconnections

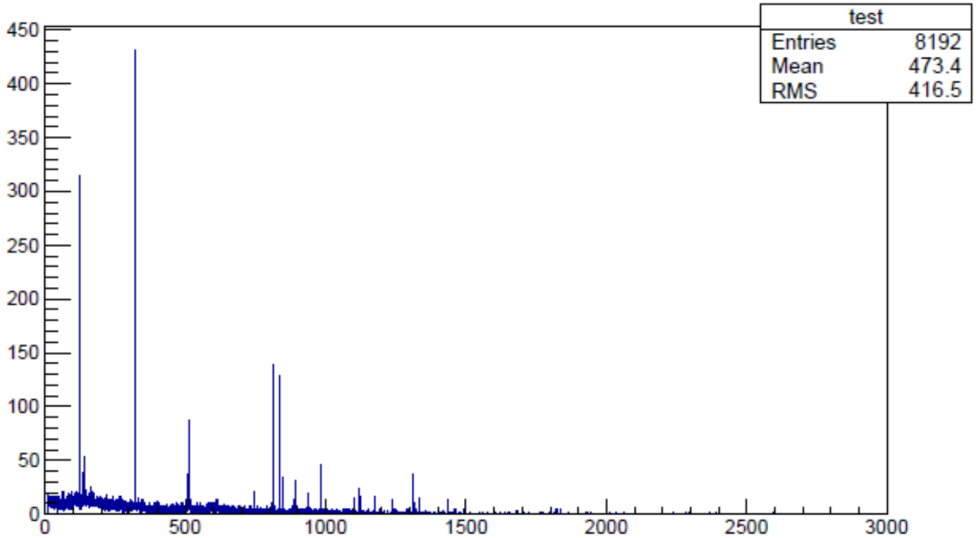
C. Adorisio and S. Roesler

CERN DGS-RP, Geneva, Switzerland

- ~100LHC Sample bags: Stainless Steel 316 L, Copper, Aluminum 6060;

  (a=0, p=2, b=6, c=5)

  LHC, irradiation time 2 years, cooling time 4 months;
- Activity is reported for : 11/9/11 8:00:00 AM



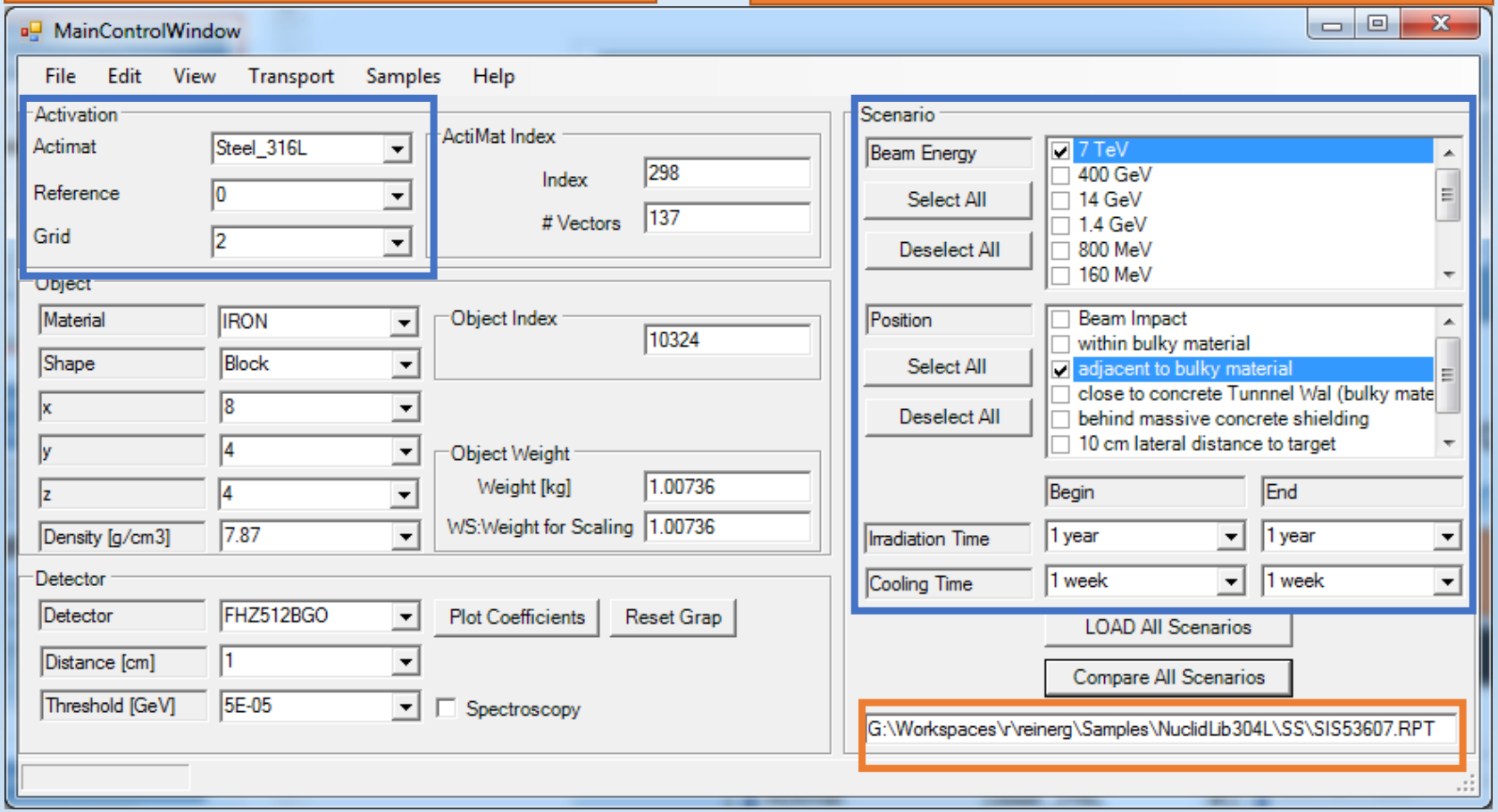
How can we combine spectroscopy & simulation? ➔Radiological Workstation (RAW)

Software combines:

- spectroscopy results.
- Radionuclide information provided by ActiWiz (software developed in RP).

> 100000 measurement setups

130 × 5630 nuclide inventories (Actiwiz)

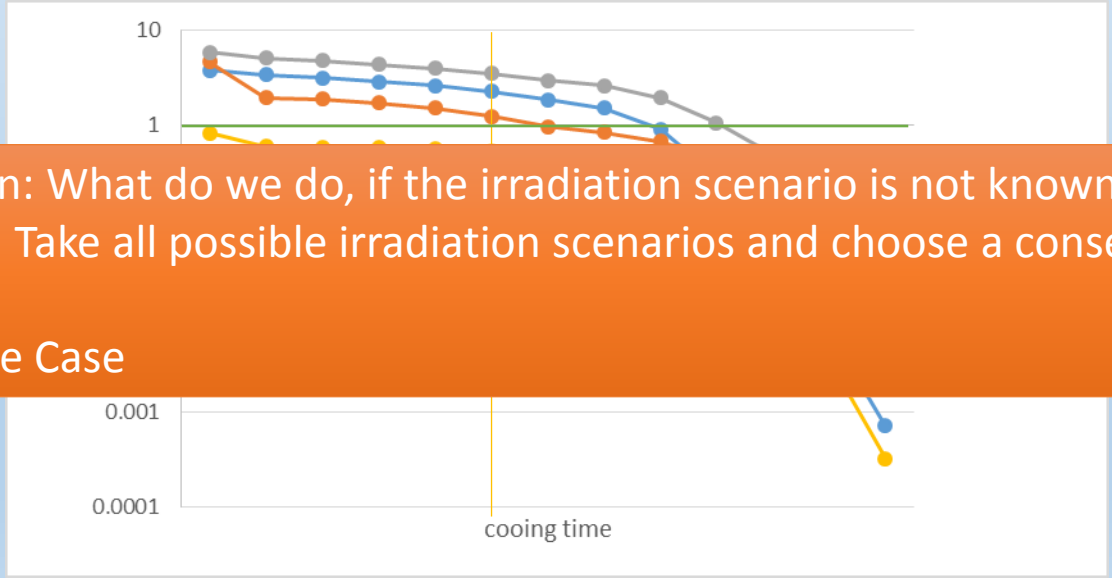


Stainless Steel Sample ST316L (ID-SIS53607): Irradiation Scenario Sc=(a=0, p=2, b=6,c=5)

N_i	LE_i	f_i	a_i^{meas}	R_i	a_i^{calc}	a_i^{mixed}	$\mathcal{R}atio_i$	$\chi^2{}_i$
units	Bq/g	(Bq/g)/(p/s)	Bq	p/s	Bq	Bq	-	-
Fe-55	30	3.82E-05	-	-	15.8	15.8	-	-
Mn-54	10	2.14E-05	7.7	359852	8.8	7.7	1.14	0.41
V-49	600	8.04E-06	-	-	3.3	3.3	-	-
Co-57	50	5.79E-06	2.7	477681	2.3	2.7	0.863	0.56
Cr-51	300	4.15E-06	0.56	135220	1.7	0.56	3.05	8.80
Co-60	1	3.50E-06	2.05	586157	1.4	2.05	0.70	4.089
Co-56	4	1.39E-06	0.36	262401	0.5	0.36	1.57	3.07
Co-58	10	6.35E-07	1.37	2163062	0.26	1.37	0.19	142.1
H-3	200	5.07E-07	-	-	0.21	0.21	-	-
Sc-46	7	5.07E-07	0.42	844197	0.21	0.42	0.48	16.21
			$\overline{R}=$	413563				

Results for a Sample Bag.
Irradiation Scenario Sc=(a=0, p=2, b=6,c=5)

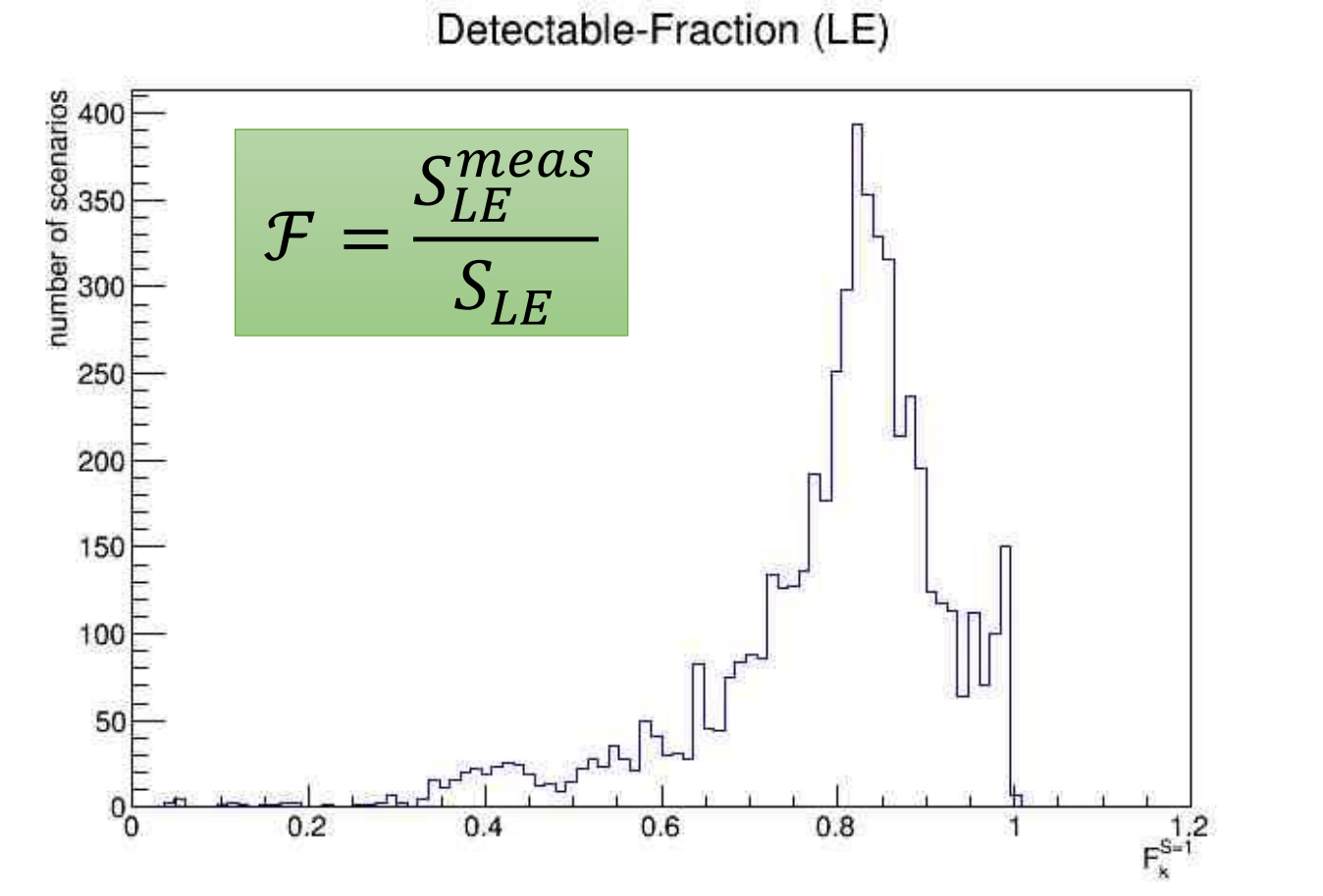
ID	Material	$\overline{R}$ [p/s]	S_{LE}^{meas}	S_{LE}^{mixed}	χ^2/n	n
SIS53607	Steel_316L	413563	3.17	3.74	25	7
SIS13739	Aluminium_6060	428537	0.439	0.50	12	3
SIS53606	Cu-OFE	502360	1.30	1.34	17	8
	Average($\overline{R}$):	~448000				
	Iron: a_i=	$f_i \cdot \overline{R}$	-	2.29		



Question: What do we do, if the irradiation scenario is not known?
Answer: Take all possible irradiation scenarios and choose a conservative limit.

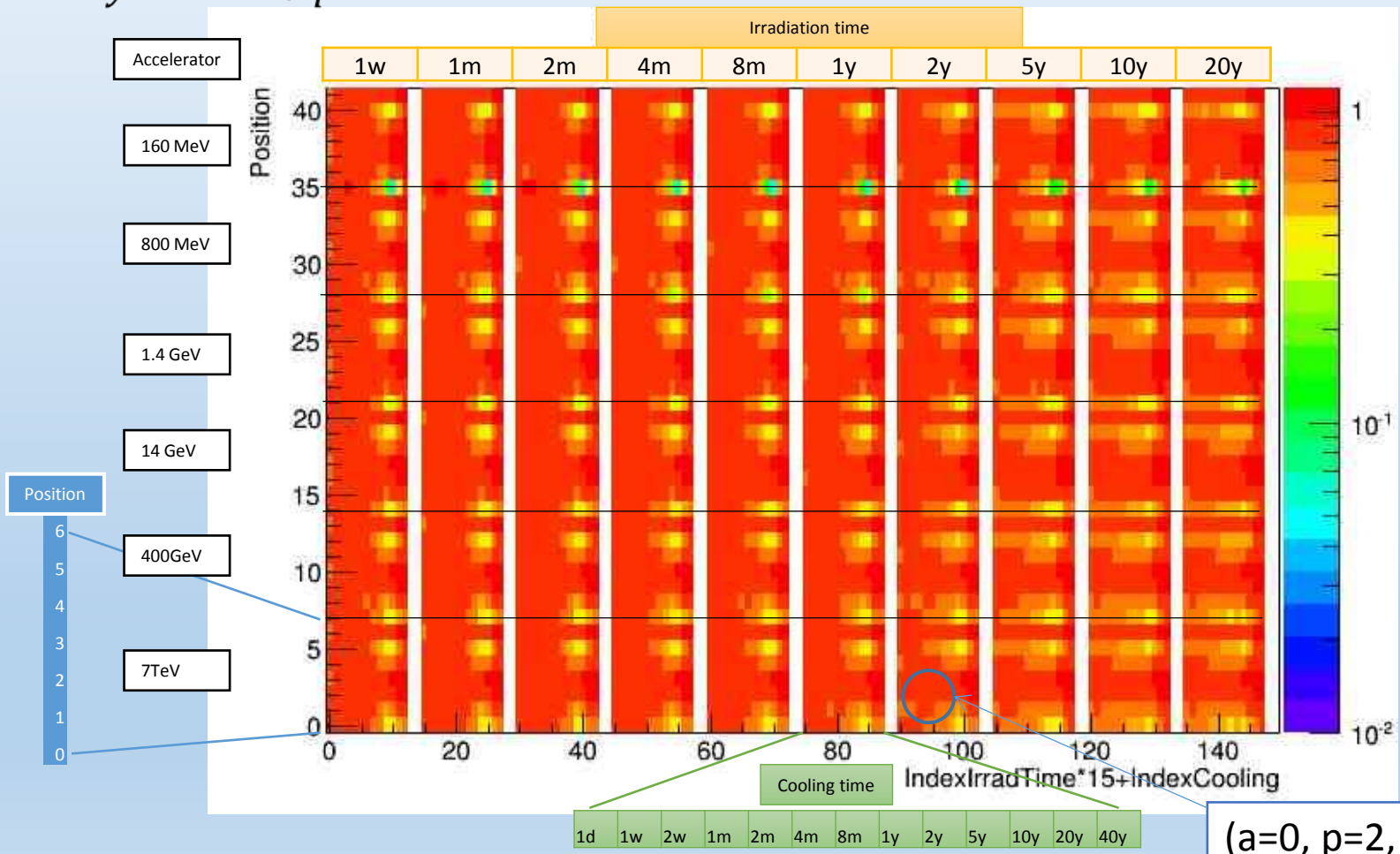
Envelope Case

Envelope of 5460 irradiation scenarios. Steel 316 L sample



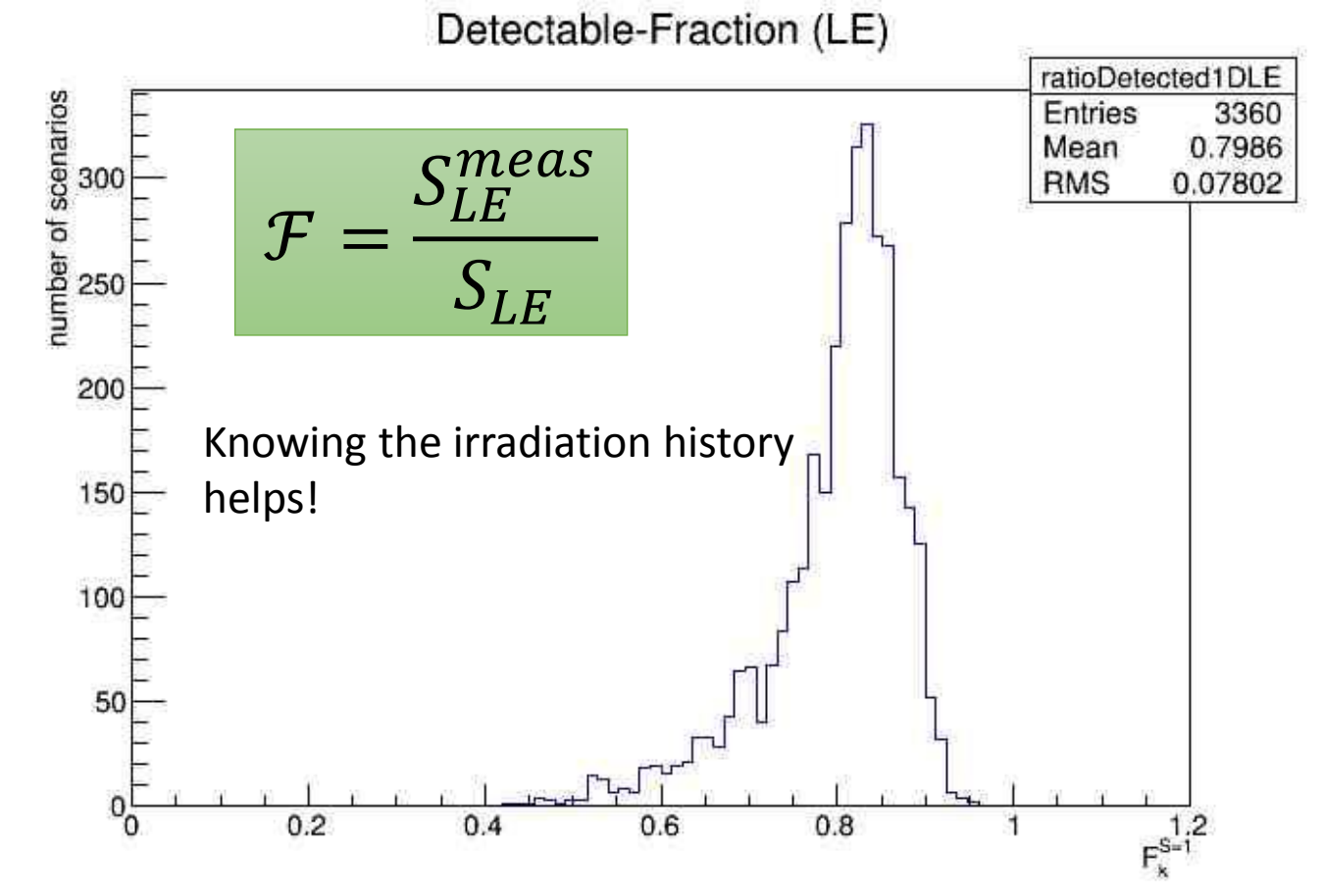
$\mathcal{F}$ – distribution of the Steel 316L Sample

$$x = 15 \cdot b + c$$
$$y = 7 \cdot a + p$$



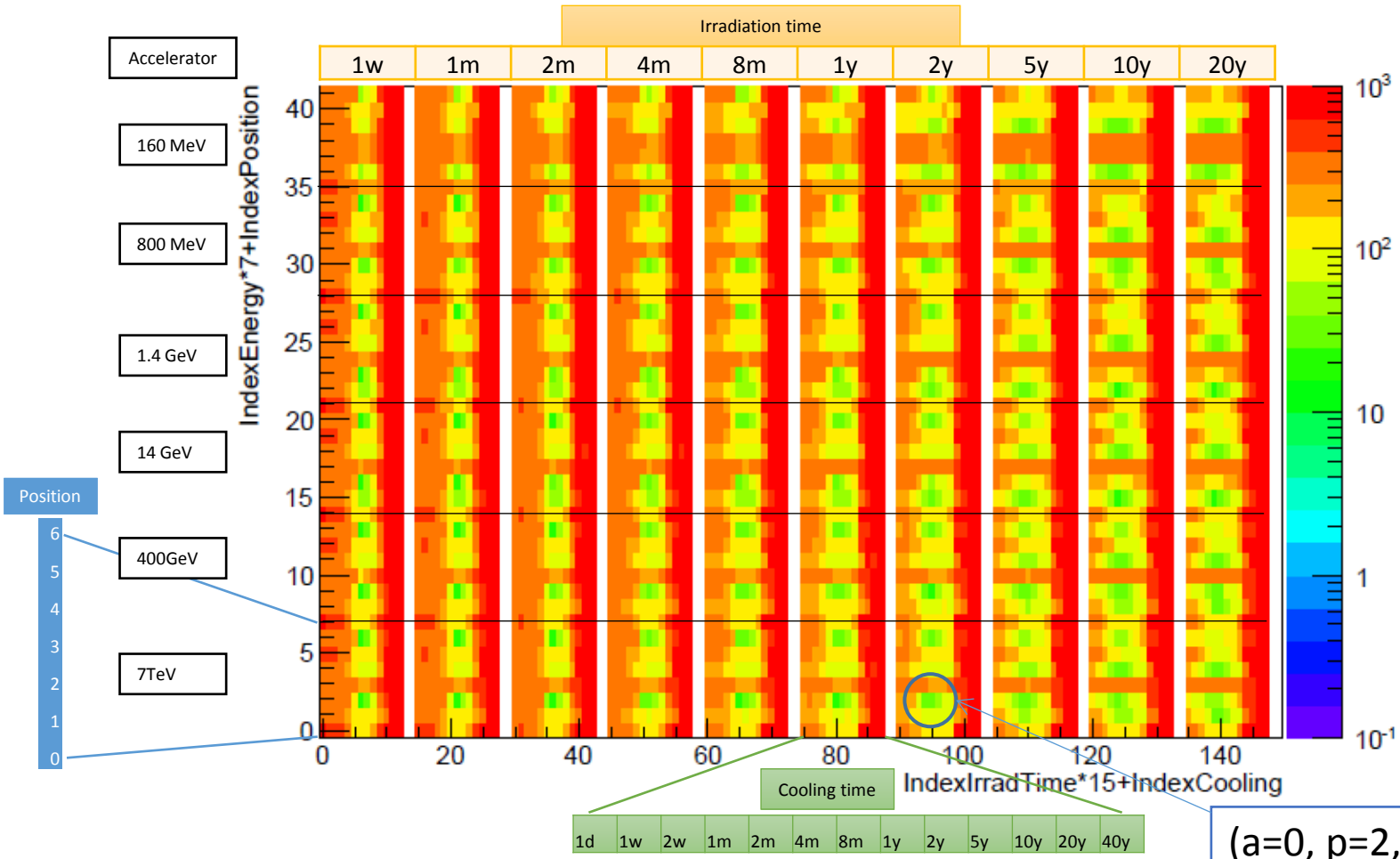
(a=0, p=2, b=6, c=5)

Envelope of irradiation scenarios with cooling times <1 year.



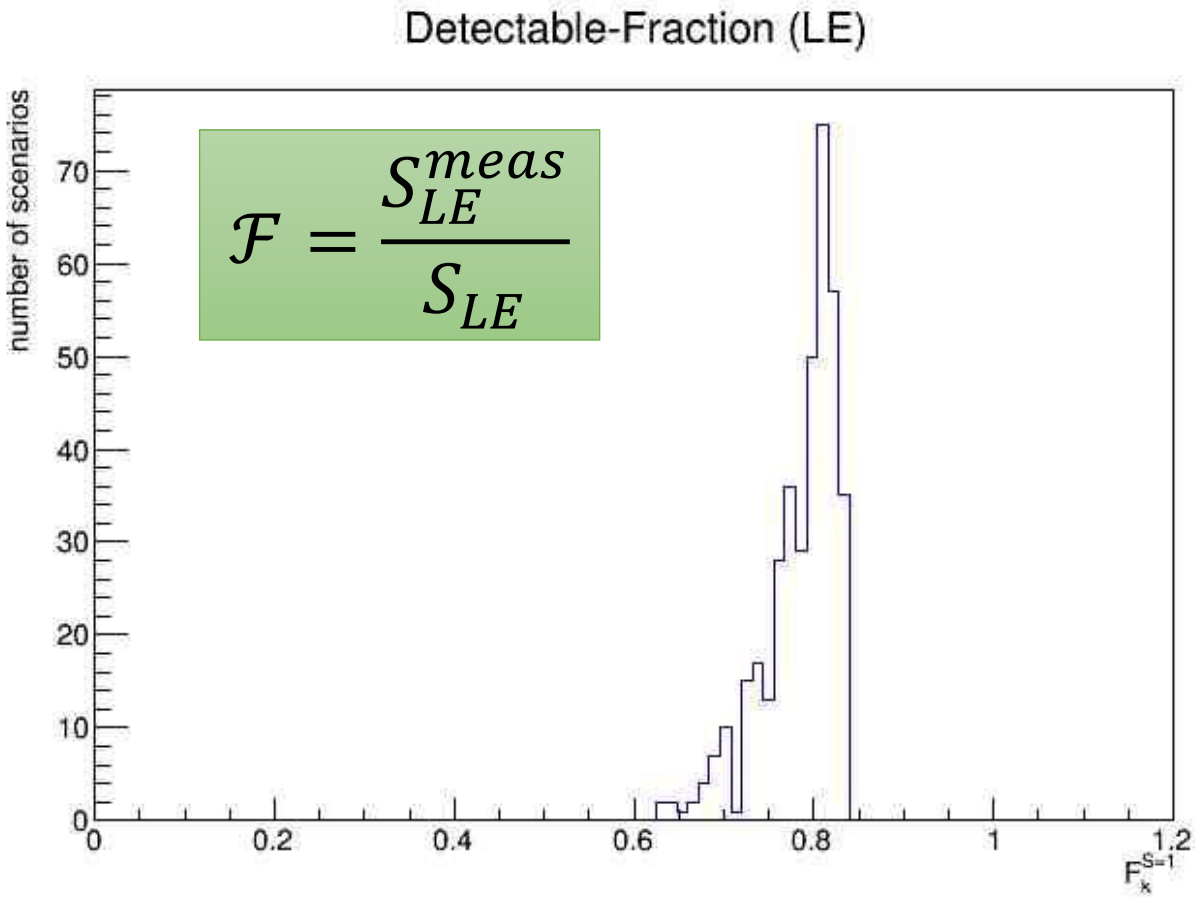
χ^2/n – distribution of the Steel 316L Sample

$$x = 15 \cdot b + c$$
$$y = 7 \cdot a + p$$



(a=0, p=2, b=6, c=5)

Envelope of irradiation scenarios with χ^2/n<50.

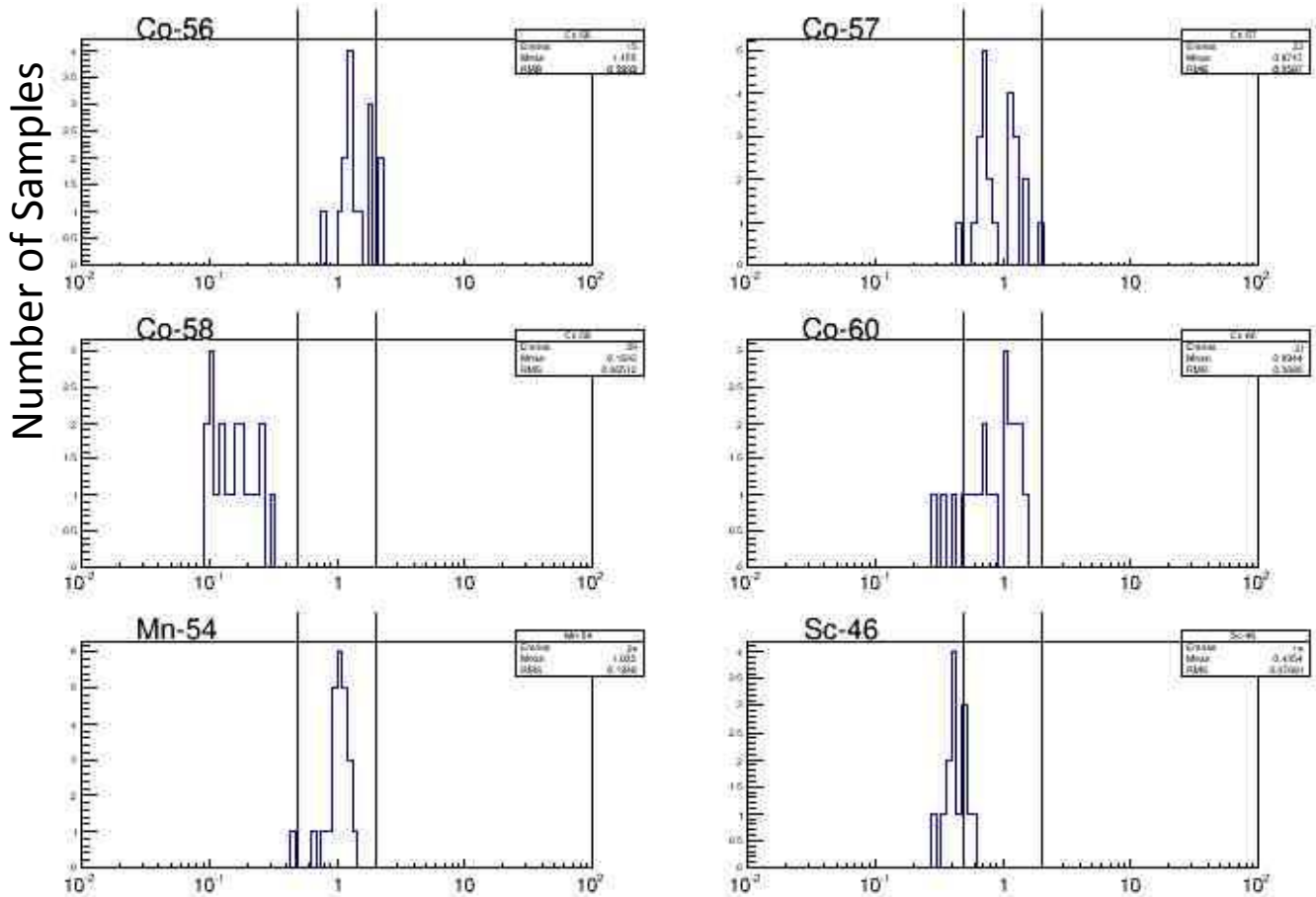


$$\mathcal{F} = \frac{S_{LE}^{meas}}{S_{LE}}$$

Why is the χ^2 important?

1. We can cross check the radiological history of a material.
2. We can identify right or exclude unsuitable irradiation scenarios in the analysis.
3. We can crosscheck the chemical composition.
4. We can validate the simulation (Actiwiz).

Benchmarking of the Simulation Model ActiWiz: ST316L



Fe-55??

$$\mathcal{R}atio_i = a_i^{calc} / a_i^{meas}$$

Sources of Errors

- Wrong assumption about the chemical composition of the material.
- Wrong assumption about the beam loss mechanism at the accelerator (irradiation field).
- Wrong assumptions about irradiation and cooling times (irradiation history).
- Error in the analysis of the spectrum.
- Cross Section in the Monte Carlo.

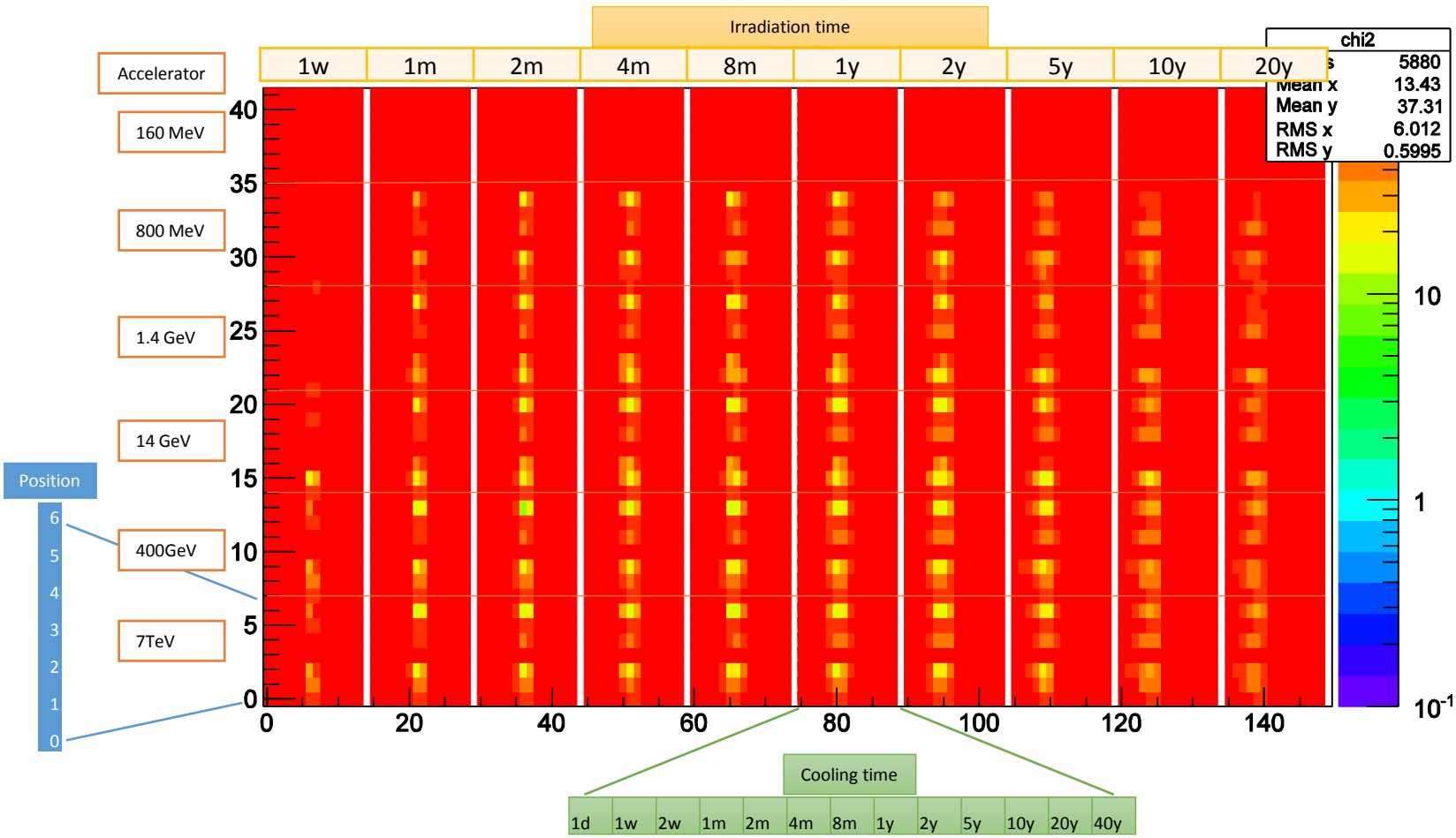
- We have to understand the errors in detail (complex task).
- RAW allows for automatized benchmarking for a large number of samples.
- Exercise should be continued for different irradiation fields and materials.

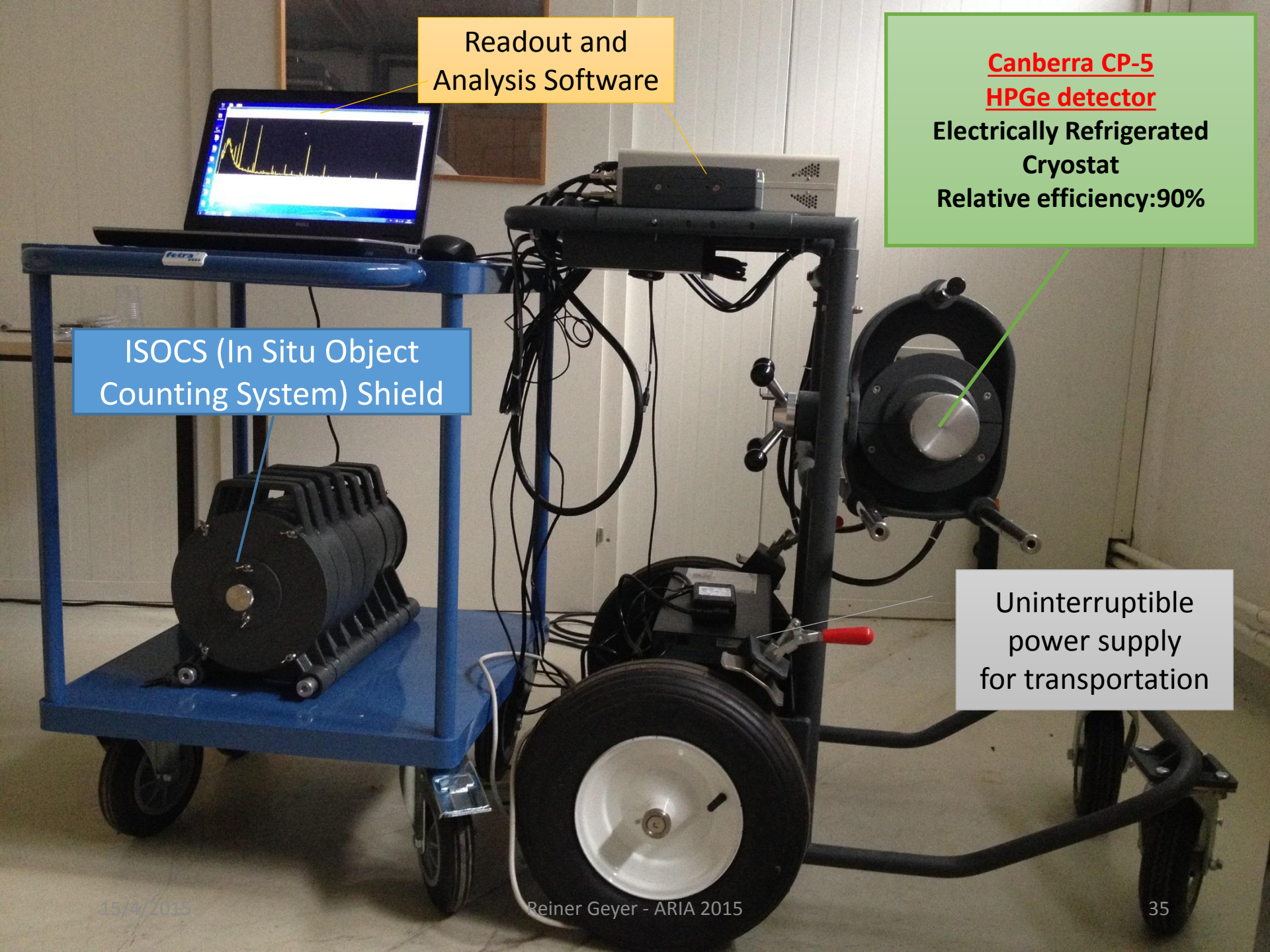
Conclusions

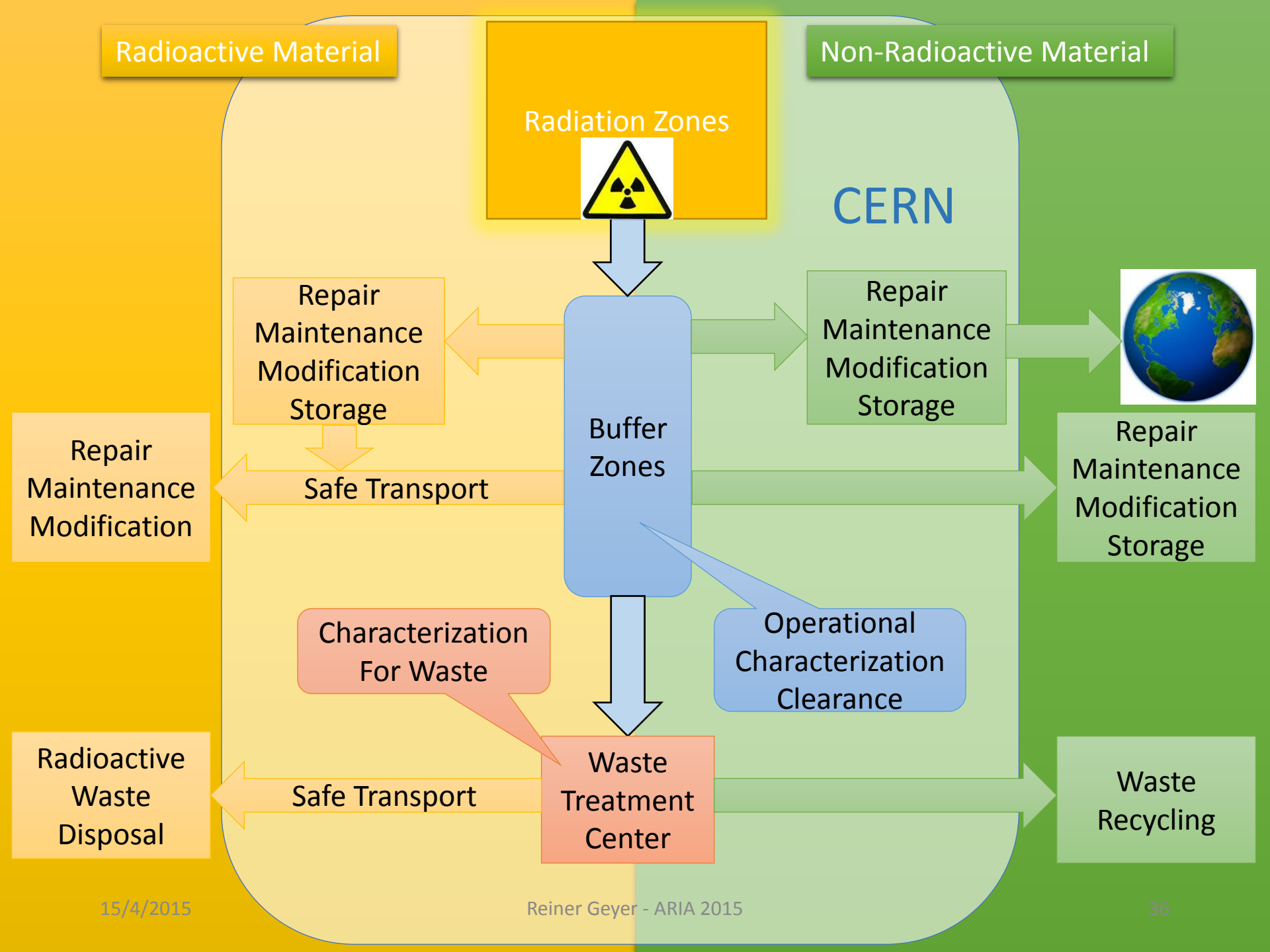
- Rate measurements and spectroscopy results are not able to deliver the complete information for the radiological characterization of materials.
- The nuclide content hast to be complemented, either by additional measurements like radio chemical analysis or by simulations.
- The present version of RAW combines measurement and simulation results. It can be used:
  - with rate measurements.
  - With spectroscopy measurements.
  - For known irradiation scenarios.
  - For unknown irradiation scenarios (envelope case).
- A good understanding of the precision of the simulation models is essential.
- First benchmark tests of ActiWiz for different materials were performed.
- These tests should be continued (different irradiation fields, nuclides and materials).
- A good knowledge about the irradiant history is very valuable and should be taken into account with the same care!

Spares

Chi-2 distribution for a simultanious analysis of 3 samples.




Readout and Analysis Software
Canberra CP-5
HPGe detector
Electrically Refrigerated Cryostat
Relative efficiency:90%
ISOCS (In Situ Object Counting System) Shield
Uninterruptible power supply for transportation


Radioactive Material
Non-Radioactive Material
Radiation Zones
CERN
Repair
Maintenance
Modification
Storage
Buffer
Zones
Repair
Maintenance
Modification
Storage
Repair
Maintenance
Modification
Safe Transport
Repair
Maintenance
Modification
Storage
Characterization
For Waste
Operational
Characterization
Clearance
Radioactive
Waste
Disposal
Safe Transport
Waste
Treatment
Center
Waste
Recycling

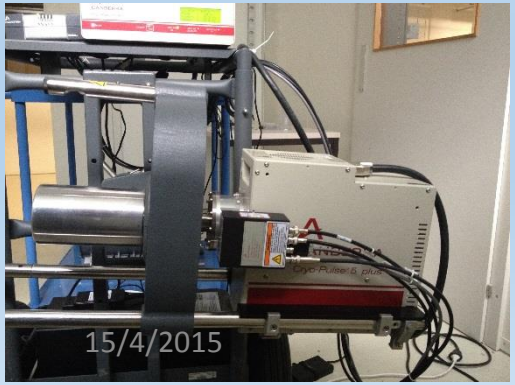
How can we adapt to the future situation?

We will need methods allowing us to:

1. cover in-situ gamma spectroscopy needs. Not all nuclides can be measured→
2. provide reasonable activation results for α , β and low energetic γ emitting isotopes.

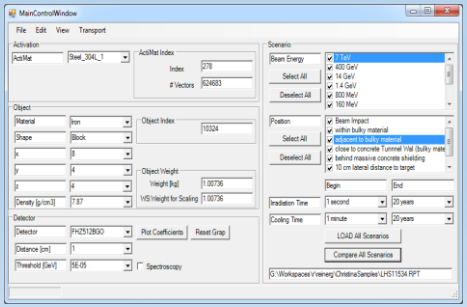
Combination of measurement and simulation results

Measuring gamma lines transportable system.



+

In-house RP software taking into account **CERN radiation fields**



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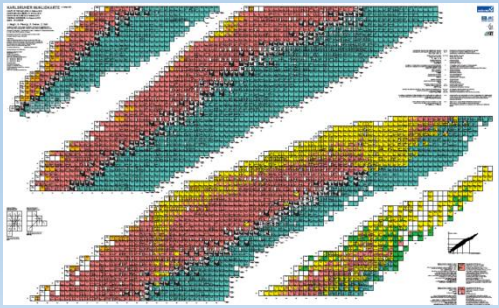
Full radio-nuclide analysis