Use of FLUKA for the analytical calculation of induced radioactivity in the CERN accelerator complex with the JEREMY code

Robert Froeschl (CERN)

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Outline

Problem description

- Beam losses lead to material activation of components of the CERN accelerator complex
- Computation of the nuclide inventory of components of the CERN accelerator complex is necessary
  - Elimination path depends on the nuclide inventory
  - Measurements for all components are too costly (time and money)
- Challenges
  - Large uncertainties in irradiation histories
  - Beam loss maps hardly exist
  - Varying material compositions
  - Isotope production cross sections at high energies

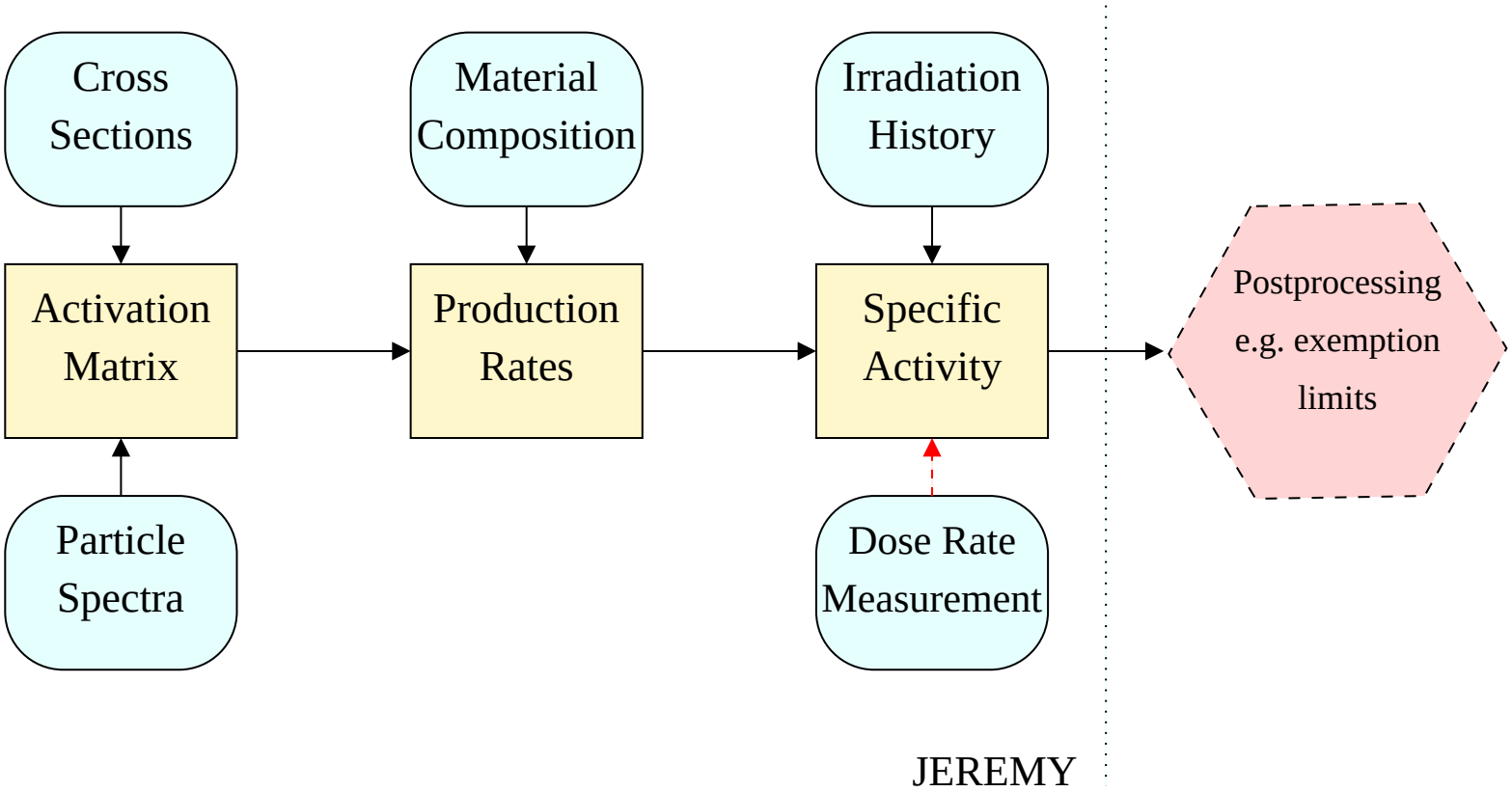
FLUKA approach

- Full FLUKA simulation with RESNUCLEi scoring
- Pros
  - Correlations are taken into account
  - Detailed description of the geometry and spatial distributions
- Cons
  - Error estimation very difficult / time consuming
  - Production and decay information cannot be easily accessed
  - Long iteration cycle

Spectra + cross section approach

- The idea is to compute the fluence spectra of the particles in the hadronic cascades via Monte Carlo simulation and fold them with the cross sections offline
- Required inputs
  - Spectra for neutrons, protons, pions and photons
  - Isotope production cross sections
  - Irradiation history
- Output
  - Isotope production rates
  - Specific activity (relative or absolute)
- Extension of PSI approach

Workflow


Cross Sections
Material Composition
Irradiation History
Activation Matrix
Production Rates
Specific Activity
Postprocessing e.g. exemption limits
Particle Spectra
Dose Rate Measurement
JEREMY

Inputs obtained with FLUKA

- Spectra for neutrons, protons, pions and photons
- Isotope production cross sections apart from low energy neutrons ($\leq$ 20 MeV)
  - For isomeres also use FLUKA approach (50% ground state, 50% isomeric state)

Matrix formalism

- Specific activity

$$A_b = \sum_r \sum_e T_{br}\, P_{re}\, m_e$$

- Isotope production rate

$$P_{re} = \frac{N_A}{M_e} \sum_{i=\mathrm{p,n},\gamma,\pi^+,\pi^-} \int \Phi_i(E)\, \sigma_{i,e,r}(E)\, dE$$

- Time evolution

$$T_{br}(t_{\mathrm{irr}}, t_{\mathrm{cool}}) = \sum_{c,r\to b} \int_0^{t_{\mathrm{irr}}} \sum_{m=1}^{j_c} c_{m,c}\, e^{-\lambda_{m,c}\,((t_{\mathrm{cool}}+t_{\mathrm{irr}})-t_0)}\, dt_0$$

$$= \sum_{c,r\to b} \sum_{m=1}^{j_c} \frac{c_{m,c}}{\lambda_{m,c}} \left(e^{-\lambda_{m,c}\, t_{\mathrm{cool}}} - e^{-\lambda_{m,c}\,(t_{\mathrm{cool}}+t_{\mathrm{irr}})} \right)$$

Error estimation

- Standard Gaussian error propagation for
  - Material composition
  - Irradiation history
  - Cross sections
  - Particle spectra
- Monte Carlo simulation

Standard Gaussian error propagation

- Derivative with respect to the material composition

$$\frac{\partial A_b}{\partial m_e} = \sum_r T_{br} P_{re}$$

- Derivative with respect to t_{cool}

$$\frac{\partial T_{br}}{\partial t_{\mathrm{cool}}} = \sum_{c,r\rightarrow b} \sum_{m=1}^{j_c} -c_{m,c} \left(e^{-\lambda_{m,c} t_{\mathrm{cool}}} - e^{-\lambda_{m,c} (t_{\mathrm{cool}}+t_{\mathrm{irr}})} \right)$$

- Derivative with respect to t_{irr}

$$\frac{\partial T_{br}}{\partial t_{\mathrm{irr}}} = \sum_{c,r\rightarrow b} \sum_{m=1}^{j_c} c_{m,c} e^{-\lambda_{m,c} (t_{\mathrm{cool}}+t_{\mathrm{irr}})}$$

Standard Gaussian error propagation

- Derivative with respect to the l-th bin $\Phi_i(l)$ of the spectrum histogram

$$\frac{\partial P_{re}}{\partial \Phi_i(l)} = \frac{N_A}{M_e} \sigma_{i,e,r}(l) \Delta E_i(l)$$

where $\Delta E_i(l) = \bar{q}_{i,l+1} - \bar{q}_{i,l}$.

- Derivative with respect to the l-th bin $\sigma_{i,e,r}(l)$ of the isotope production cross section histogram for isotope r by shooting particle type i onto element e

$$\frac{\partial P_{re}}{\partial \sigma_{i,e,r}(l)} = \frac{N_A}{M_e} \Phi_i(l) \Delta E_i(l)$$

Standard Gaussian error propagation

- Error on the induced specific activity A_b

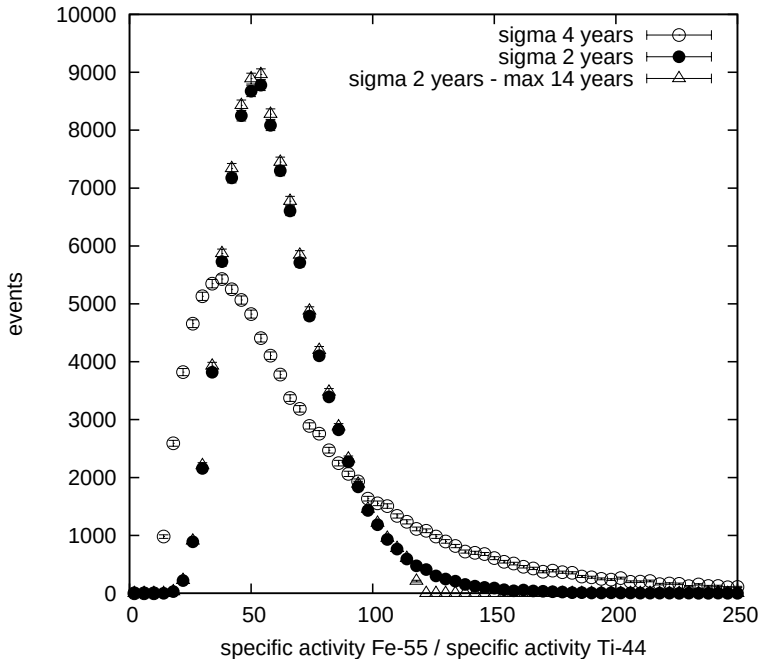
$$\sigma^2_{A_b} = \sum_{t_i,t_j=t_{\mathrm{cool}},t_{\mathrm{irr}}} \frac{\partial A_b}{\partial t_i}\,\sigma_{t_i,t_j}\,\frac{\partial A_b}{\partial t_j} + \sum_{m_{e_i},m_{e_j}} \frac{\partial A_b}{\partial m_{e_i}}\,\sigma_{m_{e_i},m_{e_j}}\,\frac{\partial A_b}{\partial m_{e_j}} +$$
$$\sum_{i=\mathrm{p,n},\gamma,\pi^+,\pi^-}\ \sum_{\Phi_i(l),\Phi_i(j)} \frac{\partial A_b}{\partial \Phi_i(l)}\,\sigma_{\Phi_i(l),\Phi_i(j)}\,\frac{\partial A_b}{\partial \Phi_i(j)} +$$
$$\sum_r\sum_e\ \sum_{i=\mathrm{p,n},\gamma,\pi^+,\pi^-}\ \sum_{\sigma_{i,e,r}(l),\sigma_{i,e,r}(j)} \frac{\partial A_b}{\partial \sigma_{i,e,r}(l)}\,\sigma_{\sigma_{i,e,r}(l),\sigma_{i,e,r}(j)}\,\frac{\partial A_b}{\partial \sigma_{i,e,r}(j)}$$

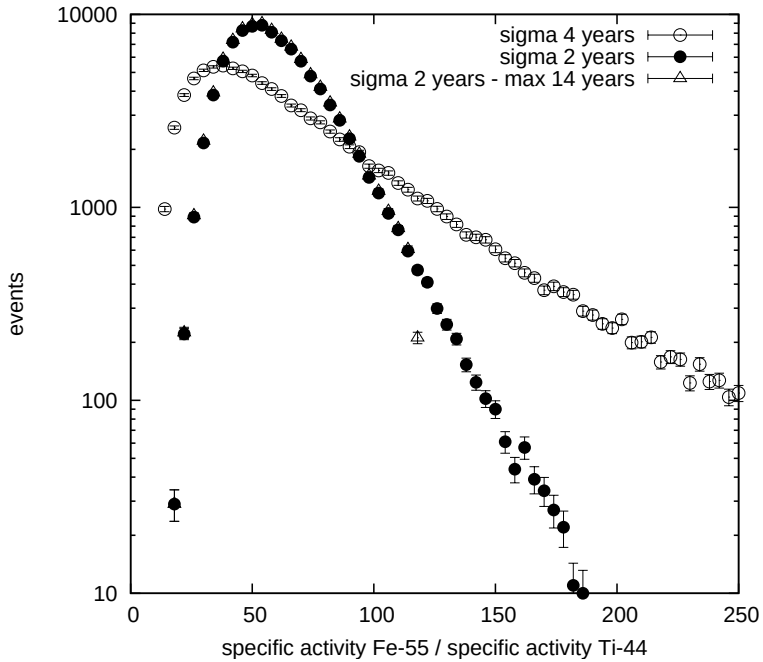
- Full covariance formalism possible
  - Correlations between spectrum bins computed with FLUKA would be nice
- Impact of individual quantities (e.g. the cross section for a given reaction) can be assessed
- Error propagation for derived quantities

Monte Carlo simulation

- Assign PDFs to relevant parameters according to their uncertainty and obtain distribtions for the specific activity
- in principle arbitrary PDFs
- all common PDFs available, e.g. gaussian, exponential
- Very fast approach (2000 events per minute)
- Distribtions of derived quantities can be easily computed

Monte Carlo simulation





Implementation of JEREMY

- Coded in Python with `numpy` package
  - Selected core routines coded optionally in `C` for speed–up
- Documented in `pydoc/html` format
- Object oriented
  - in combination with Python $\rightarrow$ powerful scripting interface, e.g. for postprocessing (exemption limits) or Monte Carlo simulation
- Isotope production cross sections
  - Low energy neutrons from JEFF 3.1.1 library (including isomere branching ratios)
  - High energy particles from FLUKA models
- Full time evolution with decay data from JEFF 3.1.1 library
- GUI (planned)

Applications of JEREMY

- Characterization and elimination of first components of the CERN SPS complex towards France this year
- Computation of the nuclide inventory for components that will be eliminated towards Switzerland for the capacity planning for the Swiss Final Repository
- Radiological classification of parts of LHC detectors
- Hadron therapy centers

Conclusions

- Improved uncertainty estimation for induced activity
- Full access to production and decay information
- FLUKA simulations heavily needed for spectra and cross sections