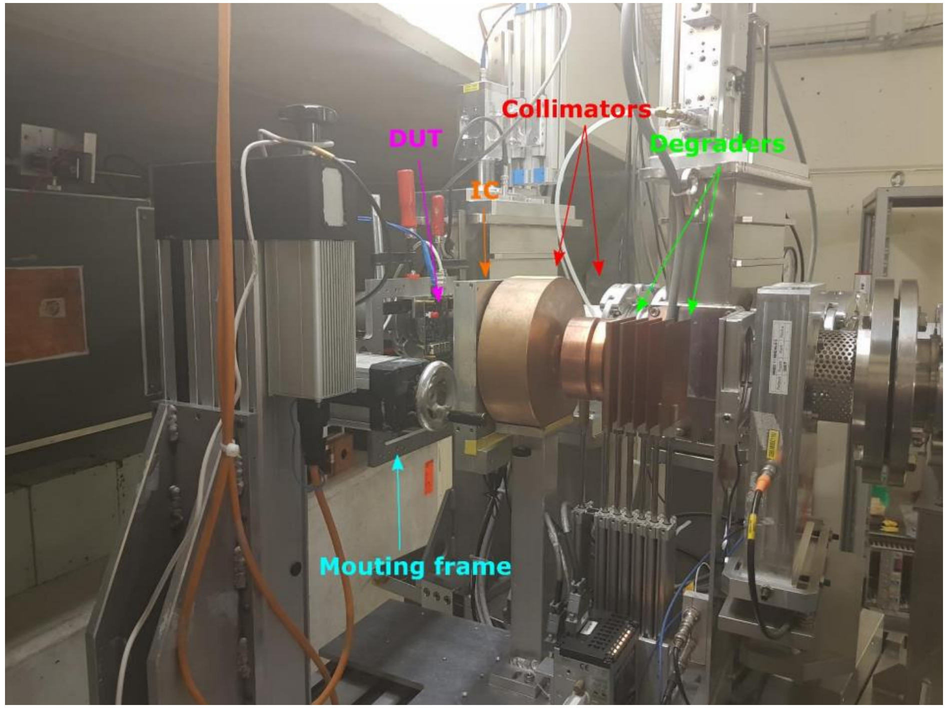
Exercise : Scoring II

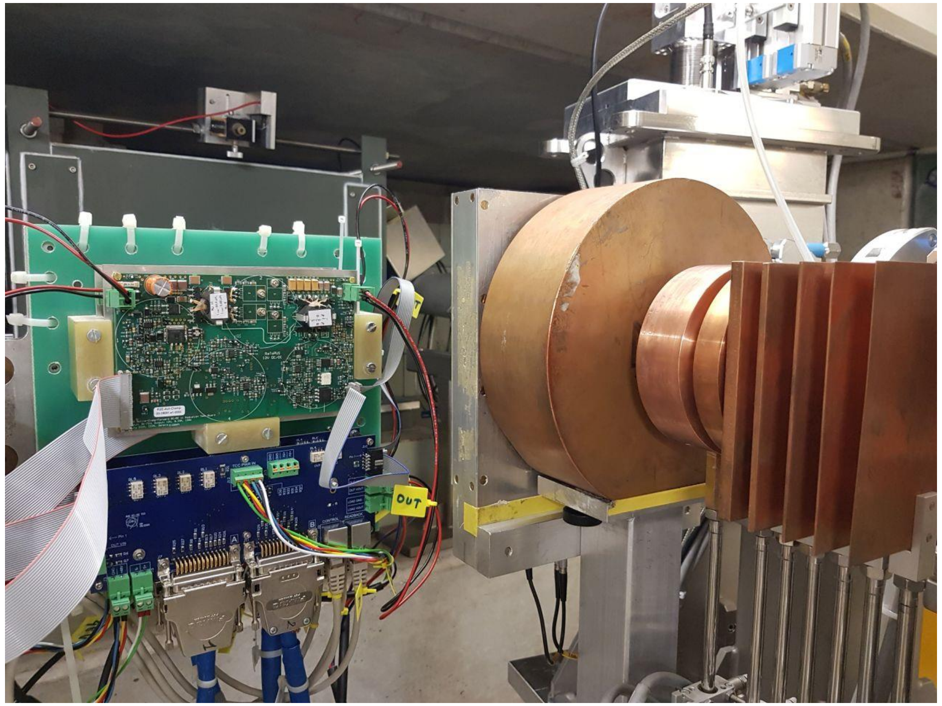
Aim of the exercise:

- Learn how to use **USRTRACK** and **USRYIELD** scoring cards
- Evaluate the impact of an energy degrader on a proton beam

Exercise inspiration



Credit: Daniel Söderström



Credit: Grzegorz Daniluk

Paul Scherrer Institute (PSI) Proton Irradiation Facility (PIF) degrader system (more info at http://pif.web.psi.ch/pif.htm)

Short intro

- Protons up to 200 MeV are very popular for radiation effects testing on electronics, mainly due to:
  - The (relatively) high availability of ~200 MeV proton cyclotron facilities, linked primarily to proton therapy
  - Their capability of inducing all three type of effects on electronics (total ionizing dose, displacement damage and Single Event Effects - SEEs)
  - Their coverage of the particle energy spectra for trapped protons in space
- Space standards require testing for SEEs in the 20-200 MeV proton energy range. Therefore, degraders are often used to modify the primary beam energy at cyclotron facilities.
- The figure-of-merit for SEE induction is the linear energy transfer (LET) in silicon. Protons in general do not induce SEEs via direct ionization (LET < 0.54 MeVcm^2/mg) but rather indirect ionization (i.e. reaction products with LET > 1 MeVcm^2/mg)

The input file

- Simplified example of the two main parts of a radiation effects on electronics simulations:
  - Simulation of radiation environment (in this case, proton beam interacting with degrader – as performed in irradiation facilities)
  - Interaction with a micro-electronic component (in this case, a thin silicon layer)
- The input file contains a 230 MeV proton beam interacting with a **49.5 mm** copper degrader, and a thin silicon region representing a micro-electronic component under irradiation
- Biasing of inelastic reactions is included in the silicon region to enhance the event statistics
- Evaporation of heavy particles is also enabled

Add these scorings and run

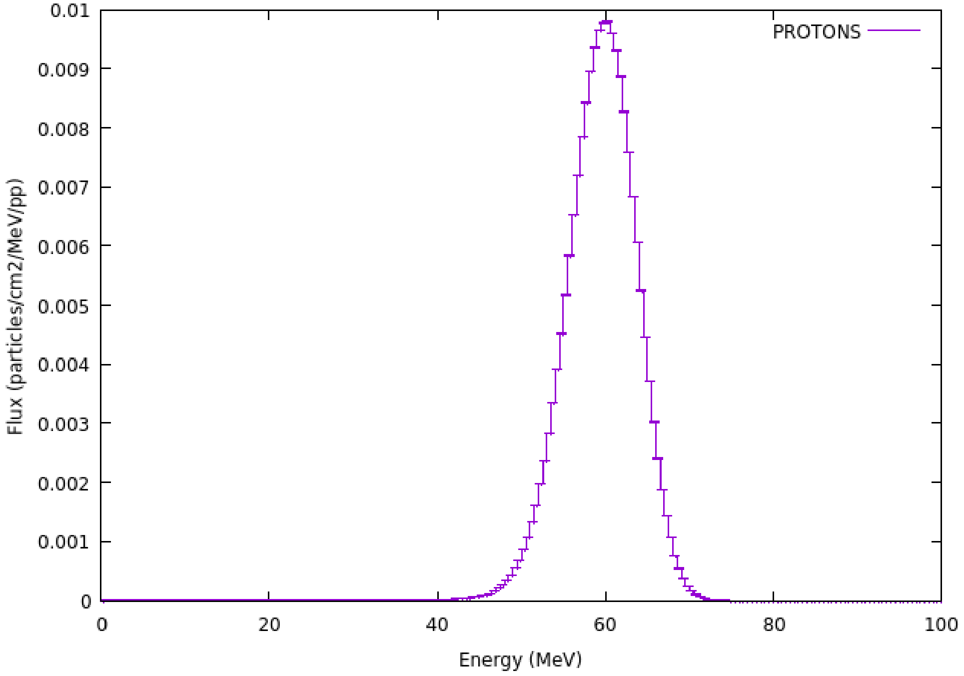
1. Proton and neutron fluence:
   - Add a **`USRTRACK`** to score the energy spectrum of protons and neutrons in the DETECT region (e.g. linear, up to 250 MeV, with 500 bins)
2. LET distribution in silicon
   - Add a **`USRYIELD`** to score LET of particles travelling from DEVICE to VOID (e.g. up to 5000 keV/(μm×g/cm^3), which corresponds to 50 MeVcm^2/mg)
     - Scoring kind needs to be set to **d2N/dx1dx2**, and material to **silicon**
   - Use the range of the 2nd variable to score (i) the total LET distribution (i.e. all particles), and (ii) the LET for a charge (i.e. Z) of 2, and 12 (use half-integers as limits!)
3. Run 10 cycles of 10^4 primaries each
4. Plot the **`USRTRACK`** results for protons in linear y-axis scale, and protons and neutrons in logarithmic y-axis scale, in units of differential flux (reminder: divide by detector volume if not explicitly included in scoring card!)
5. Plot the **`USRYIELD`** results in logarithmic y-axis, including the total, Z=2 and Z=12 distributions (reminder: multiply by the bin width of the second variable of USRYIELD)
6. Bonus: run same simulation but with different degrader thickness (e.g. **41.4 mm, 53.5 mm**) and check impact on results

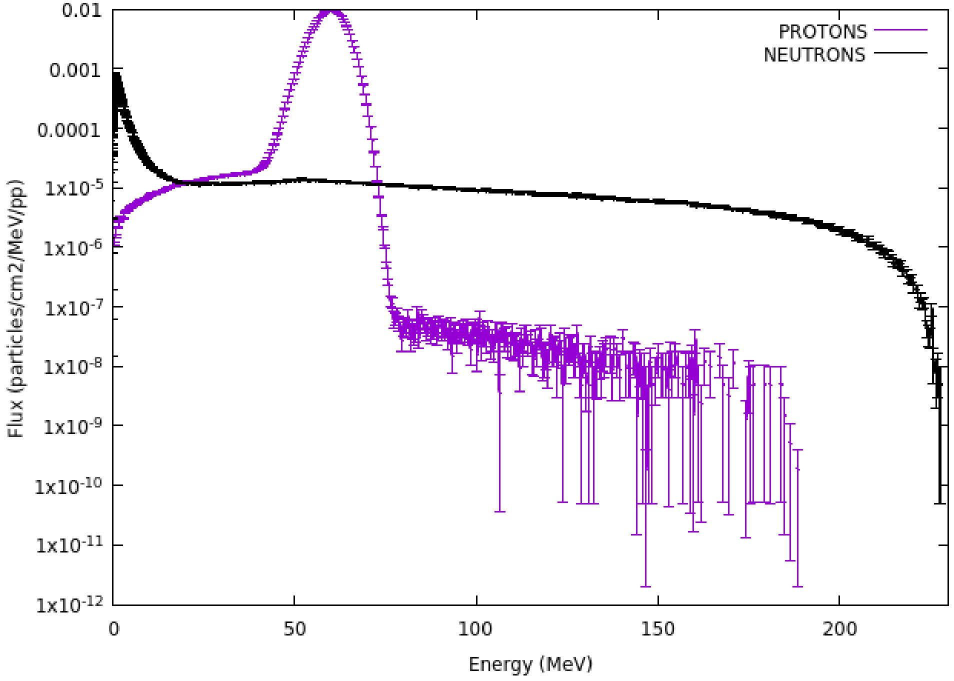
Questions that can be answered from looking at generated plots

- What is the impact of the degrader in terms of (i) the shift of the average beam energy, (ii) the introduction of beam energy spread and (iii) the generation of secondary particles (i.e. neutrons)?
- What is the LET (in silicon) distribution of fragments leaving the DEVICE region? What is the maximum LET value produced?
- What is the contribution from Z=2 and Z=12 particles to the total distribution?

Result – 1 : proton and neutron spectra

- What is the impact of the degraded in terms of the (i) shift of the average beam energy, (ii) introduction of beam energy spread and (iii) generation of secondaries?

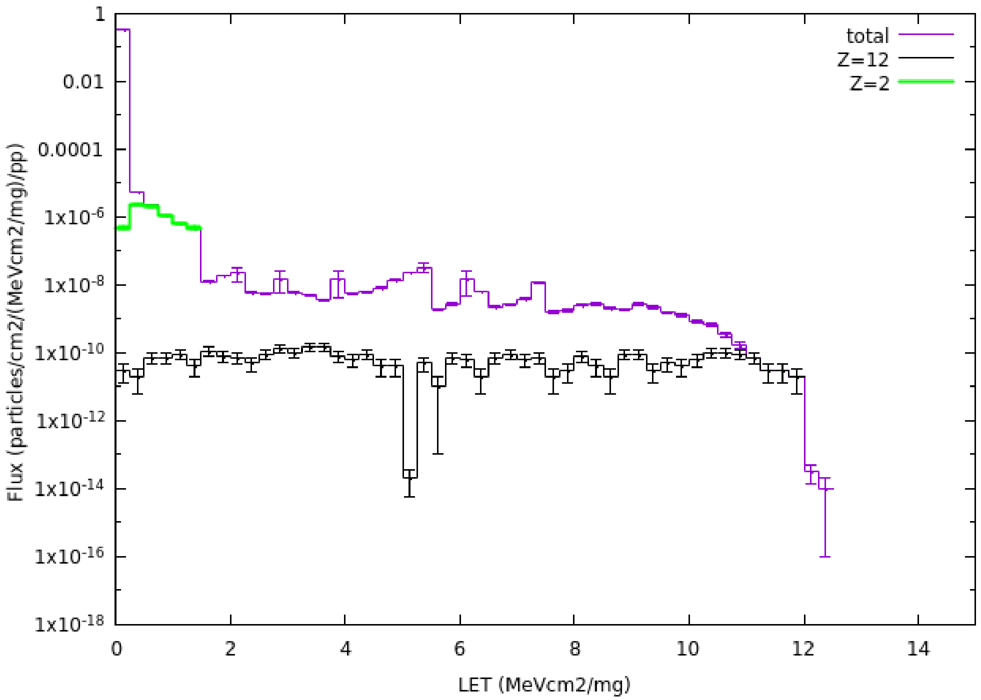




For 10^8 primaries (CPU time per primary ~0.58 ms)

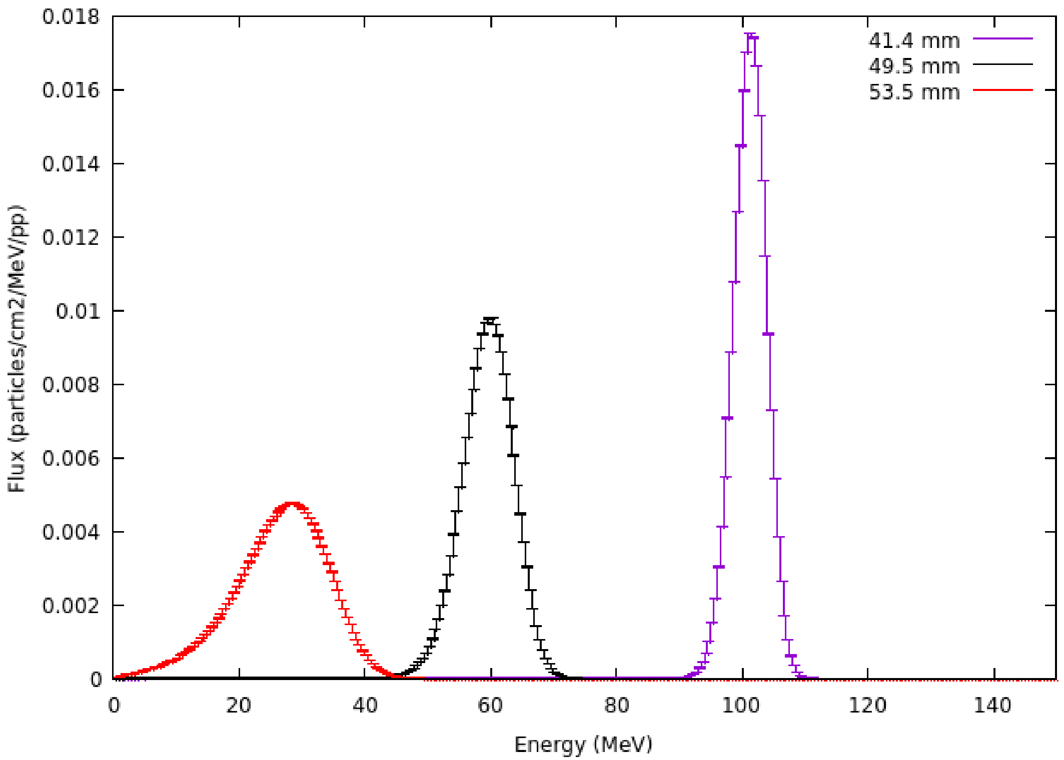
Result – 2 : LET spectra

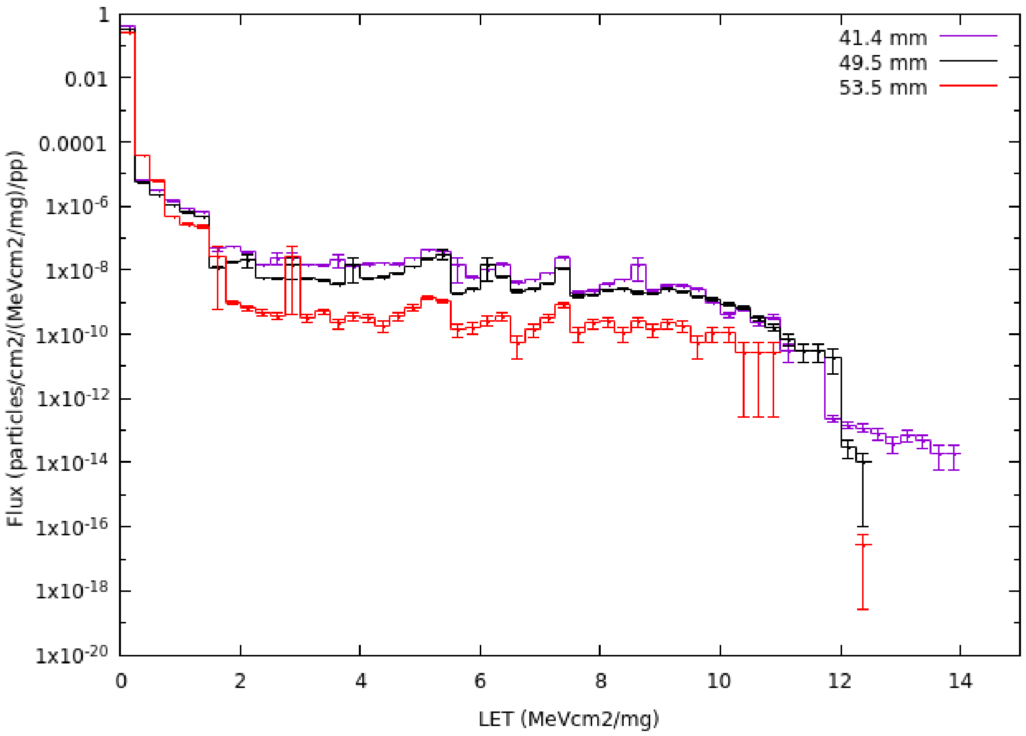
- What is the LET (in silicon) distribution of fragments leaving the DEVICE region? What is the maximum LET value produced?
- What is the contribution from Z=2 and Z=12 particles to the total distribution?



For 10^8 primaries (CPU time per primary ~0.58 ms)

Result – 3: impact of degrader thickness

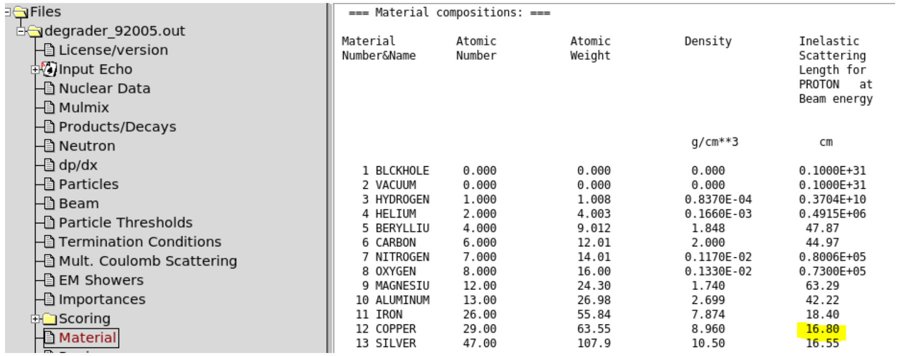




For 10^8 primaries (CPU time per primary ~0.58 ms)

Some additional results from simple post-processing

Copper degrader thickness (mm)	Average Energy (MeV)	Relative Transmitted Flux	Neutron flux (relative to protons)
41.4	100.8	0.46	2.43×10^{-2}
49.5	59.3	0.40	3.69×10^{-2}
53.5	26.4	0.34	4.80×10^{-2}



Material Number&Name	Atomic Number	Atomic Weight	Density	Inelastic Scattering Length for PROTON at Beam energy
			g/cm**3	cm
1 BLCKHOLE	0.000	0.000	0.000	0.1000E+31
2 VACUUM	0.000	0.000	0.000	0.1000E+31
3 HYDROGEN	1.000	1.008	0.8370E-04	0.3704E+10
4 HELIUM	2.000	4.003	0.1660E-03	0.4915E+06
5 BERYLLIU	4.000	9.012	1.848	47.87
6 CARBON	6.000	12.01	2.000	44.97
7 NITROGEN	7.000	14.01	0.1170E-02	0.8006E+05
8 OXYGEN	8.000	16.00	0.1330E-02	0.7300E+05
9 MAGNESIU	12.00	24.30	1.740	63.29
10 ALUMINUM	13.00	26.98	2.699	42.22
11 IRON	26.00	55.84	7.874	18.40
12 COPPER	29.00	63.55	8.960	16.80
13 SILVER	47.00	107.9	10.50	16.55

Inelastic interaction length of 200 MeV protons (primary beam) in copper: 16.80 cm

$$T \sim e^{-x/\lambda} = 0.78$$

Roughly 22% of the beam is lost due to inelastic interactions of the protons in the copper. The remaining flux reduction is due to the beam scattering in the degrader.

Some conclusions

- Degraders are useful for modifying the primary beam energy at cyclotron facilities, however:
  - They introduce a large energy spread (especially for large initial to final energy ratios)
  - They produce secondary particles (in our example, <5% with respect to primary beam flux)
  - They reduce the flux of the beam (inelastic interactions + scattering)
- Secondary particles produced are the main radiation field constituent in spallation facilities (i.e. interaction with targets as opposed to degraders)
- As expected, high-LET fragments (i.e. those most threatening for SEEs) are mainly those with high mass (i.e. target-like)

Some further applications and considerations

- Monte Carlo simulation of radiation environment and its interaction with matter (e.g. electronics) is a very useful (and powerful) tool in the domain of radiation effects
- More detailed and realistic simulations for Single Event Effect calculations require:
  - An accurate description of the component geometry (metallization and insulator regions, etc.)
  - A realistic description of the sensitive volume geometry and response function (e.g. extracted from technological information, SEE results, TCAD simulations…)
  - An event-by-event energy deposition distribution scoring, and its folding with the response function (currently, requires advanced scoring in FLUKA – related GitLab repository available for this)

FLUKA