Low energy ions tracking in Geant4

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Low energy ions tracking

- Tracking of ions is killed by geant4 when energy < 1 keV
  - i.e. when E < 1 keV all the energy is released in the gas and tre tracking stops
  - we use pre-defined `em_option4` physics list that is recommended for low energy tracking BUT
  - from Geant4 manual: “tracking of low energy ions is not accurate below 1 keV/u (atomic mass units)”
    ➜ 4 keV for helium, 12 keV for carbon, 19 keV for fluorine, etc...
  - could not force this 1 keV threshold manually (in theory cross sections are defined from 0 eV)
- Step length (dx) can be reduced as small as you like BUT
  - track is terminated anyway when energy reaches 1 keV
  - length of the last step is the maximum length set by user and not the particle remaining range
    ➜ track length is wrong (especially for few keV ions)
  - last step should be forced to have the remaining range length
- Energy deposit (dE)
  - implemented quenching factor calculated from SRIM to save the ionising fraction
  - there is also a geant4 method to retrieve “ionising” energy fraction ➜ not accurate at E<1 keV/u

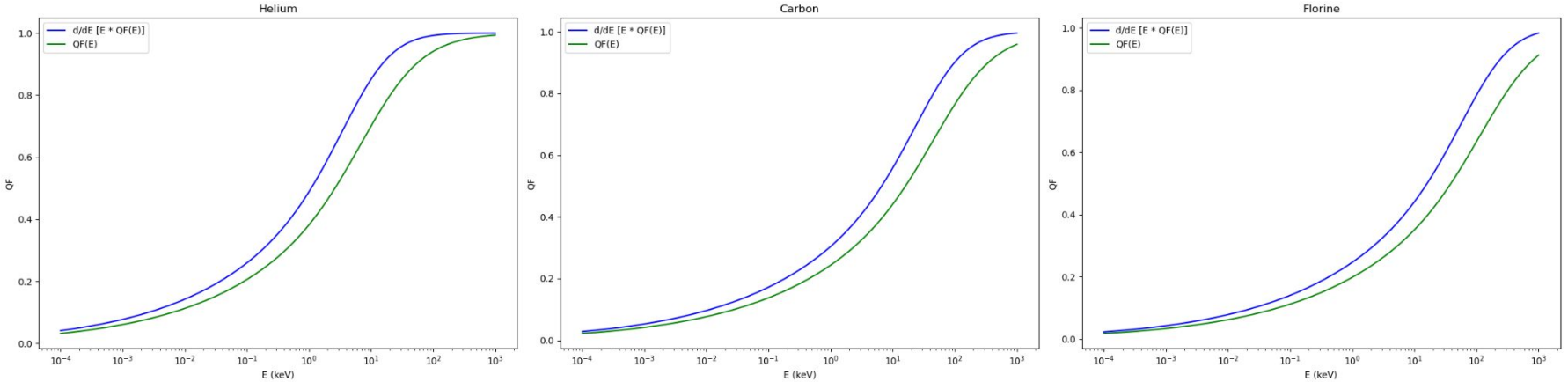
QF using SRIM parameterization

- QF from SRIM implemented in Geant4 (only for He, C, F)
- Parameterized with a function (from Flaminia's PhD thesis)

$$QF(E) = \frac{k(E_{ion} + aE_{ion}^{b})}{1 + k(E_{ion} + aE_{ion}^{b})}$$

Ion	k	a	b	χ^2/ndf
H	0.65 ± 0.02	1.82 ± 0.08	0.48 ± 0.04	40.35/20
He	0.117 ± 0.005	3.9 ± 0.2	0.44 ± 0.03	20.94/20
C	0.0195 ± 0.0007	14.7 ± 0.4	0.33 ± 0.1	36.53/20
F	0.0083 ± 0.0002	27.4 ± 0.7	0.303 ± 0.008	16.74/20

$$F(E) = \frac{d(E \times QF(E))}{dE}$$ → used to calculate hit-by-hit dE_{ion} (corrected with QF)



Geant4 code updates

- Code wip in my fork: https://github.com/gdimperi/CYGNO-MC/tree/lime

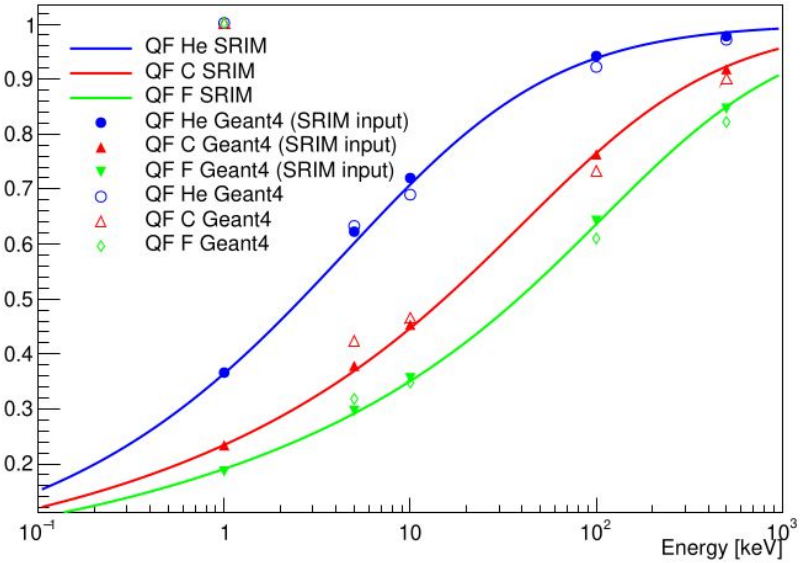
In addition to:
`energyDep` → tot energy deposited by all particles in the sensitive gas
`energyDep_NR` → tot energy deposited by ions in the sensitive gas
`energyDep_hits` → tot energy deposited by any particle in a single hit in the sensitive gas

New set of variables:

`energyDep_NRQF` → tot ionising energy (SRIM QF) deposited by an ion in the sensitive gas
`energyDep_NRQF_geant` → tot ionising energy (Geant4 QF) deposited by an ion
`energyDep_hits_NRQF` → ionising energy (SRIM QF) deposited by an ion in a single hit
`energyDep_hits_NRQF_geant` → ionising energy (Geant4 QF) deposited by an ion in a single hit

Closure test for QF

- QF calculated by geant4 with SRIM input is accurate (for He, C, F)
- QF calculated by geant4 using internal method for ionising energy is in agreement with SRIM down to ~10 keV (< 1 keV the method is not working at all)



Summary

- We plan to produce samples of NR for different purposes (AmBe, training of ML analysis, ...)
- Quenching factor (He, C, F) has been implemented in Geant4 using SRIM tables
- Range not yet checked in detail, but there is a known bug in the last step, when E < 1 keV
- Optimal solution: use both dE and dx from SRIM and create a custom physics list for low energy ions tracking. We should have the necessary tables for He, C, F (Flaminia's SRIM simulations)