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Notes on the fluence normalisation based on the NIEL scaling hypothesis [1]

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It is well known by now that the basic problems connected with radiation damage effects to be expected for silicon detector applications in future HEP experiments come mainly from bulk defects and are due to displacements of the lattice atoms and their further dynamics. The observed deterioration effects depend on the fluence, particle type and energy. Considering the produced primary knock-on atom as the main responsible for the damage, the first interaction is relevant, and the physical quantity describing it, is the NIEL (Non Ionising Energy Loss)[2] transfer, due to the primary particle fluence.

Practically, nowadays, scaling with the NIEL is considered reliable for most materials and particles and the corresponding damage functions (energy dependent displacement KERMA) values are useful to normalize the different effects expected from various particles over large energy regions.

In detector testing for the LHC silicon R&D work, we have come upon the practical problem of damage projections for future experiments. To establish a set of universal damage parameters, we need standardization, we need to use a common language of normalisation, via the NIEL hypothesis. Several "damage functions" can be found in literature, and a huge amount of experimental data have accumulated during the years. However, putting an order in the results is all the same a difficult task, due esentially to experimental details.

1 The scaling of damage effects

Relevant quantities describing the damage produced by high fluence particle beams used in the study of performance degradation of silicon detectors (e.g. the current related damage coefficient or other) are related by mathematical dependences to the fluence, of simpler or more complicated forms. In a very simplified picture we could state that the damage effects are proportional to the fluence of the particle beam generating the damage.

The NIEL scaling can be reduced to the definition of the 1 MeV equivalent neutron fluence which produces the same damage as an arbitrary beam with a certain spectral distribution $\phi(E)$ and of fluence Φ:

$$\Phi_{eq}^{1MeV} = \kappa\Phi \tag{1}$$

κ is called the hardness parameter and is defined as:

$$\kappa = \frac{EDK}{EDK(1\ MeV)} \tag{2}$$

with EDK the energy spectrum averaged displacement KERMA:

$$EDK = \frac{\int D(E)\phi(E)dE}{\int \phi(E)dE} \tag{3}$$

[1] This note presents the status by the end of 1999, and does not include any reference to NIEL in oxygenated silicon.
[2] For introductory reading, see [1].

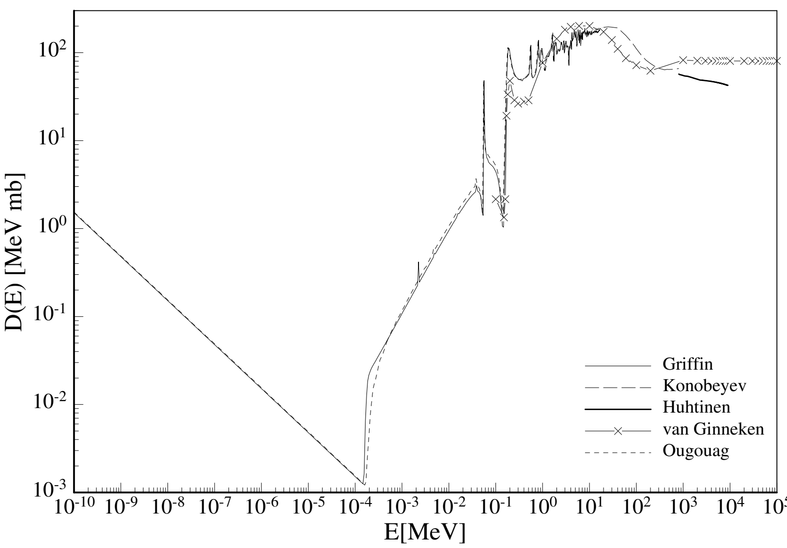

Figure 1: Displacement damage functions for neutrons in silicon

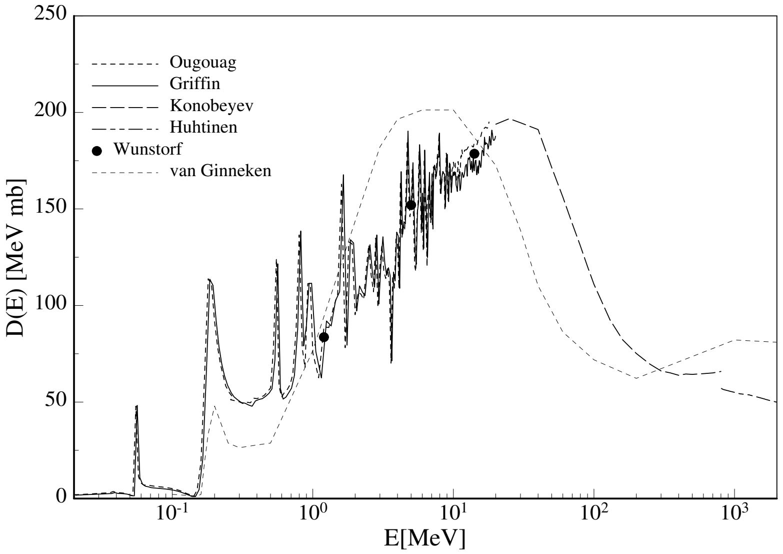

Figure 2: Displacement damage functions for neutrons in silicon: comparison with experiment

where $\phi(E)$ is the differential flux and

$$D(E) = \sum_k \sigma_k(E) \int dE_R f_k(E, E_R) P(E_R) \tag{4}$$

the displacement KERMA or the damage function for the energy E of the incident particle, σ_k the cross section for reaction k, $f_k(E, E_R)$ the probability of the incident particle to produce a recoil of energy E_R in reaction k, and $P(E_R)$ the partition function (the part of the recoil energy deposited in displacements). EDK(1 MeV)=95 MeV mb [2]. The integration is done over the whole energy range.

2 Damage functions and comparison with experimental data

The scaling recipe seems to work well for hadrons (neutrons, protons, pions), while for leptons (electrons, muons) and gammas, the experimental data is not that supportive.

Without claiming a complete experimental support coverage, several plots have been produced and are presented below, to compare the different displacement damage functions:

- For neutrons: figs. 1 and 2
- For protons: fig. 3
- For pions: fig. 4
- For electrons: fig. 5

A few comments are necessary.

In the case of neutrons, we find in literature several sets of displacement damage function data in silicon. For the lower energy range we have references like Lazo [3], Ougouag [4] and Griffin [5], up to about 20 MeV, next we find tables from Konobeyev [6], up to 800 MeV, and end with Huhtinen [7] in the GeV region. A tabulation by van Ginneken [8] was quite popular in the community during the years, now it is considered outdated, so it is just added as illustration. For the low energy region the tabulations by Lazo, Ougouag and Griffin are almost equivalent, and continuously improving as updates, so clearly the most recent ones [5] are to be considered. This choice is also supported by the experimental comparison with data obtained from monoenergetic sources, like those presented in [9], given in fig. 2. At higher energies, monoenergetic neutron sources are not available, so the discussions are more in the theoretical and phenomenological field, and considerations as smooth interpolations have been also used as practical solutions. We have previously proposed an experiment with a quasimonoenergetic neutron beam at about 20 MeV, to be obtained in a reaction by deuterons on a Trithium target. In preliminary tests at PTB Braunschweig we obtained unfortunately a neutron beam of only about 19 MeV, and an undesired "background" between 1 and 8 MeV, using a deuteron beam of 2.69 MeV. This gives us only the confidence, within the accuracy of our experiment, that the Griffin tabulations are verified at the upper limit of the dependence described by them, but did not serve as a decisive test for the choice of damage functions above 20 MeV.

There is a "step" discrepancy in the 400–800 MeV energy region, at the end of the Konobeyev curve, compared with the data given by Huhtinen; one of our sources for the tabulations suggests the above mentioned smooth interpolation as a practical solution [7], from 400 MeV, neglecting the relative constant last part of the Konobeyev curve, to 800 MeV where the next data set starts. The solution looks reasonable, but we should not forget that the curve given by Huhtinen results from semiempirical considerations and fits on experimental data. No other extensive calculations have been made for energies higher than the typical reactor physics energy region. It is possible however that the data from [14] are somewhat underestimating the damage at energies above 800 MeV by up to 10%, in case we consider an extrapolation of Konobeyev's curve, with the behaviour we see for the region between 400 to 800 MeV. As a last comment, comparing the low energy end of the Konobeyev curve with the Griffin data, we see the Konobeyev values again higher, by between 7% to 3.3%, at 15 and 20 MeV, respectively.

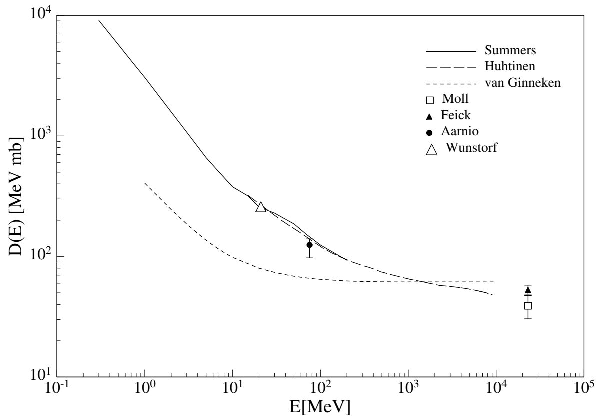

Figure 3: Displacement damage functions for protons in silicon, comparison with experiment

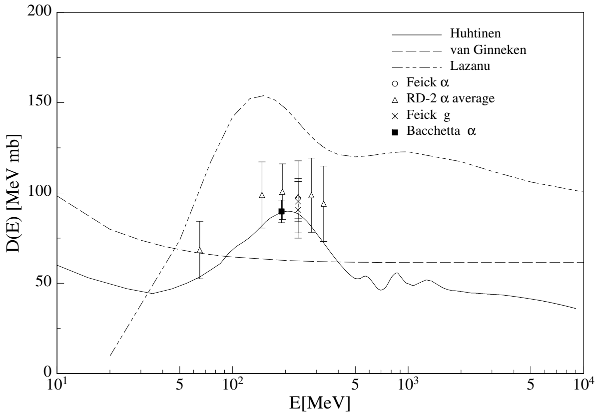

Figure 4: Displacement damage functions for pions in silicon, comparison with experiment

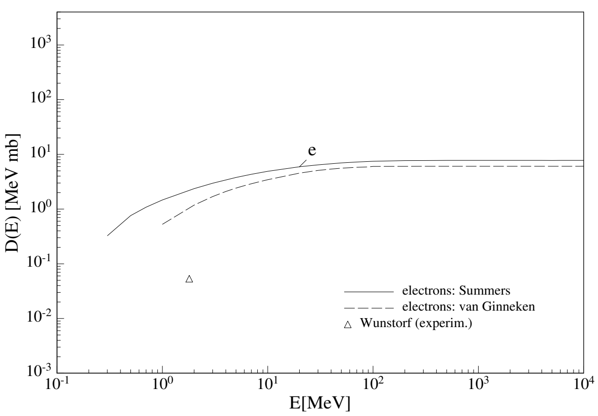

Figure 5: Displacement damage by electrons in silicon

For protons, the discussion refers only to 3 sets of data: Summers [10] and Huhtinen [7], with an interpolation between the limits of the data sets at 2 and respectively 15 MeV energy values, and the old data from van Ginneken [8]. Experimental data we find by Wunstorf [9] for 21 MeV, and Feick [11] and Moll [12], for 23 GeV protons. The latter two points prove that the tendency of the proton damage curve is extrapolating the Huhtinen data, and not the old data from van Ginneken, which did not take into account spallation, for instance.

The case of pions is even more controversial. As a first remark, we note that the damage data have no statement related to the charge state of the pion, which however has an effect in the scattering cross section of these particles on nuclei (the shape and position of the nuclear resonance are different, depending on the charge state of the pion, positive or negative!). We have up to our present knowledge 3 sets of displacement damage tabulations, due to van Ginneken [8], Lazanu [13] and Huhtinen [14]. The van Ginneken data are just a vague approximation, neglecting totally the presence of the Δ resonance. Lazanu's calculations are based on a compilation of pion-nucleus experimental cross-sections, but as we can see from fig. 4, the values plotted overestimate by about a factor of 1.5 the experimental values. Our choice goes to the last set of damage function data [14], keeping in mind however that this is also the result of a semiempirical method, which does not claim a very high accurary, but is a professional estimate, based on proton and neutron damage data, and phenomenological considerations.

Coherent measurements to allow unambiguous hardness factor (κ) determination are quite hard to find. We have analysed several publications and the choice of the illustration with experimental data can be argued, but the reasons for our choice was to reduce to minimum experimental variabilities not taken into account or difficult to correct or normalise for.

It is also worth a comment why one would illustrate NIEL dependence with experimental values of different damage parameters (current related or N_{eff} related). It is a matter of taste maybe, but both approaches have certain pros and cons. Current related damage is a linear effect, and hence simpler, but has the inconvenient of being highly temperature dependent and the main uncertainties occur due to its annealing. The processes related to the evolution of the effective doping concentration are more complex.

As to electrons, there is a question mark whether we may use the same "language" of normalisation as for the hadrons. From figure 5 we can see quite a discrepancy with the only experimental point we present. We have the feeling that damage effects due to leptons and gammas are to be discussed separately, and that the problems include taking into account the aspect of the type of defects produced by these particles, which is not the same as for hadrons, and for which the NIEL scaling made an approximation of a constant multiplicative factor, and hence neglected. So, while NIEL scaling with energy for one particle type might work well for all of the particles in the whole energy range (if the nature of interaction does not change essentially as type of defects produced with energy), most probably the independence of particle type of the scaling in general can be questionable.

3 Recommendations and impact on LHC experiments

To summarize, we consider reasonable to recommend the use of the NIEL scaling with the damage functions presented in fig. 6. For the main tabulations, see [18].

The impact of the uncertainties mentioned in this note on the LHC environment is fortunately moderate. The particle spectra are typical like the ones from fig. 7, which presents an example of fluence levels expected in silicon detectors in the ATLAS central tracking detector.

The most important part to worry about as to damaging particles is represented by the high fluences of neutrons, typically in the barrel detectors and by pions in the pixel layers. The spectra used in this representation have been taken from A. Ferrari and correspond to those considered in the ATLAS Technical Design Report [19].

A folding with the presently recommended damage functions for neutrons and pions, gives the lethargy plots in fig. 8. (This type of representation has the advantage of illustrating suggestively the damage to be expected, by proportionality of the area under the curves with the damage. Normalisation has been done to 1 MeV neutron equivalent damage).

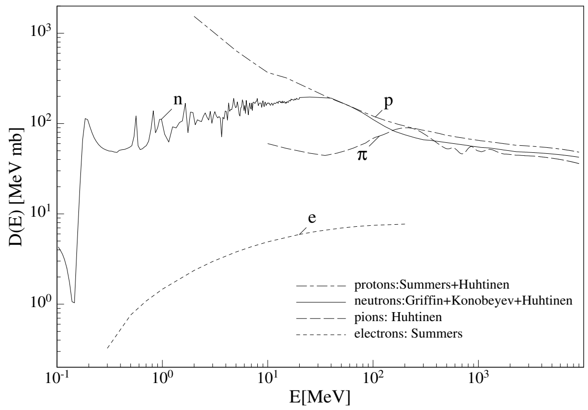

Figure 6: Recommended displacement damage functions for NIEL scaling in silicon

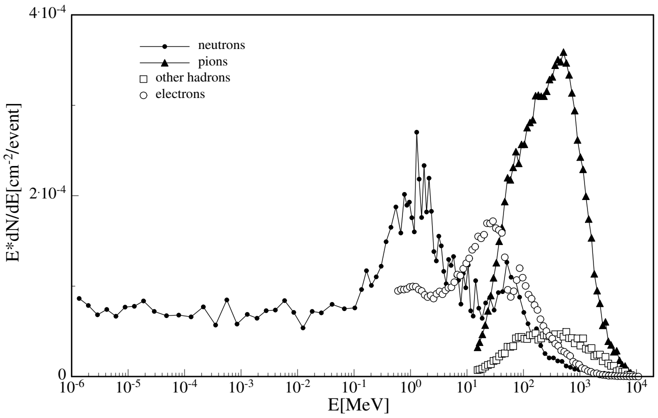

Figure 7: Expected particle spectra in the ATLAS silicon detector at the LHC

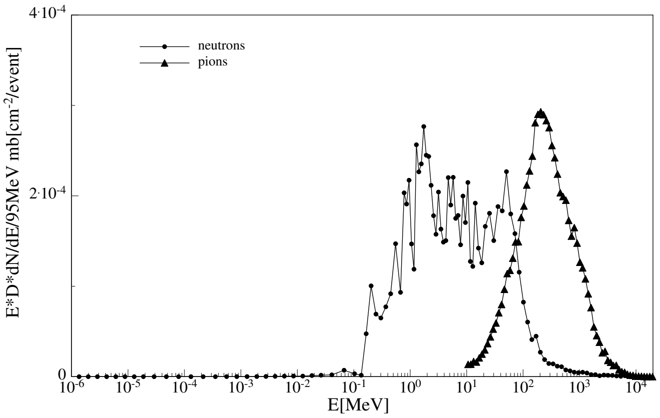

Figure 8: Impact of displacement damage to silicon detectors in ATLAS

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