attacked by performing studies at elevated temperatures thus accelerating the kinetic effects being responsible for such long-term changes. Related basic studies are found in Refs. [8–10].

3. NIEL scaling of bulk damage

The preceding discussion and numerous experimental observations have led to the assumption that damage effects produced in the silicon bulk by energetic particles can be described as being proportional to the so-called displacement damage cross-section D. This quantity is equivalent to the NIEL and hence the proportionality between the NIEL value and the resulting damage effects is referred to as the NIEL-scaling hypothesis (for deviations to this rule see Section 4.5.1). The displacement damage cross-section D is normally quantified in MeV mb, whereas the NIEL value is given in keV cm^2/g. For silicon with $A = 28.086$ g/mol the relation between D and NIEL is $100\,\mathrm{MeV\,mb} = 2.144\,\mathrm{keV\,cm^2/g}$. The D or NIEL value is depending on the particle type and energy. According to an ASTM standard, the displacement damage cross-section for 1 MeV neutrons is set as a normalizing value: $D_n(1\,\mathrm{MeV}) = 95\,\mathrm{MeV\,mb}$ [11]. On the basis of the NIEL scaling the damage efficiency of any particle with a given kinetic energy can then be described by the hardness factor κ. Applying the NIEL hypothesis, one may replace the actual particle energy spectrum $d\Phi/dE$ by a NIEL folded spectrum and the damage effect, caused by its total fluence Φ_p by a 1 MeV neutron equivalent fluence $\Phi_{eq} = \kappa \cdot \Phi_p$; a more detailed discussion is found in Refs. [12,13].

In Fig. 2 the normalized NIEL values are plotted as function of energy. The data are taken from Refs. [14–17]. More recent calculations can be found in Refs. [6,18]. NIEL scaling and its limitations is extensively discussed in Refs. [6]. Regardless of possible deviations in certain cases, the NIEL scaling should always be applied as a first-order approximation of the damage efficiency. Hence, it is useful to display the NIEL folded energy spectra for the most abundant particles (neutrons and pions) in the LHC experiments, as done for the SCT region of ATLAS in Fig. 3 [12]. Finally, the resulting equivalent fluences as function of radius are shown in Fig. 4.

Fig. 2. Non-ionizing energy loss NIEL for different particles.

Fig. 3. NIEL folded energy spectra for neutrons and pions in the SCT region (silicon counter tracker) of the LHC ATLAS detector.

From Fig. 3 we conclude that reactor neutrons, ranging mainly from 1 to 10 MeV, are adequate for reliable damage tests and that indeed irradiations with 250 MeV pions, available at PSI-Villigen, should result in similar damage as expected in LHC. Many of the past and present irradiation tests have however been performed using the 23 GeV proton beam at CERN-PS. In