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Overview on the radiation environment in ATLAS and CMS SCT and the irradiation facilities used for damage tests[1]

Angela Vasilescu

INPE, Bucharest, POB MG-6, R-76900; E-mail:angela@roifa.ifa.ro

The majority of the published papers on radiation hardness studies start with affirmations on the doses and particle fluences estimated in the interaction region and in the detectors, giving figures like tens of MGy for the dose and 10^{14} n/cm^2 for the neutron fluence for 10 years of LHC operation at nominal parameters.

Radiation hardness tests have to be performed at radiation sources and irradiation facilities, well characterised concerning fluxes and spectra, temperature and secondary radiation, which should assure reproducible geometry and spectra, with precise measurement of the irradiation fluence. Ideal would be a source to simulate or allow an easy extrapolation, as much as possible to the actual experiments. Certainly such a requirement cannot be achieved so simply; it is considered that the spectra used can be equivalent with an 1 MeV neutron spectrum, on the basis of the NIEL (Non-Ionising Energy Loss) scaling hypothesis, presented in detail in [1, 2].

To apply the NIEL scaling we need a complete understanding of all the radiation sources, in a detailed study. This paper presents the principal sources used in radiation hardness testing of silicon detectors, together with the simulated spectra for the LHC experiments.

1 Radiation levels at colliders

At a luminosity of 10^{34} cm^{-2}s^{-1}, assuming an inelastic cross-section[2] of 80 mb, LHC will produce on average $8{\times}10^8$ pp inelastic events per second, creating an extremely hostile radiation environment. For the radiation hardness studies, the pulsed structure of the LHC beam is not significant. The only scaling parameter for dose and fluence is the inelastic interaction rate. A nominal year corresponds to 10^5 pb^{-1}.

There are three major radiation sources at the LHC:

- primary particle production
- local beam losses
- beam–gas interaction.

Total beam losses at the LHC should be less than 10^7 protons/s, a small value compared to the collision rate of 10^9 s^{-1} at each interaction point. Beam–gas interactions are estimated to $\sim 10^2$ m^{-1} s^{-1} in the interaction regions. The main source remains for sure the primary pp interaction.

Secondary particles will produce material degradation in the detectors and activation of the different components.

Most of the particles produced in the primary interactions are absorbed in the calorimeters, where they deposit large quantities of energy, but those coming from the shower tails and from backscattering can affect the muon spectrometers and the central tracker. The shower tails contain mostly neutrons, photons and electrons. They contribute to the counting rates and to the degradation of the detectors, but, in principal, radiation defects are produced by hadrons of high energy and energy loss, and less

[1] This report summarizes a part of the PhD Thesis [1] presented in 1997 at IAP Bucharest (in Romanian). For general reference, a summary of the thesis is available in English. A second part of the thesis, closely related to this overview is the NIEL chapter, available as another report [2].

[2] Most recent extrapolations for the non-diffractive cross-section at $\sqrt{s}$=14 TeV are situated between 65 and 70 mb. However the older value of 80 mb is preferred in the calculations.

by thermal neutrons or photons. Activation is due to spallation products of the high energy hadrons in showers, as well as to neutron capture.

The Monte–Carlo calculations of the isodoses in the detectors performed by different authors follow the same recipe: minimum bias events are generated with the DTUJET[3] code for the pp interaction, which are further propagated with the FLUKA transport code [4] for secondary particles. Some calculations use combinations of DTUJET + GCALOR[5]. Differences in results are below 30%.

Simulations with DTUJET + FLUKA have been compared to experimental results [6, 7] and the total uncertainty due to minimum bias and cascade generation was found to be less than 30%.

All particle rates are normalised to a luminosity of 10^{34} cm^{-2} s^{-1}, and for one nominal year of 10^7 s the integral is 10^{41} cm^{-2}.

1.1 The ATLAS detector

Table 1 presents maximum dose and fluence rates per year in different components of the ATLAS detector, after [8].

The inner detector (containing silicon detectors, and thus of special interest in this work) is exposed to intense neutral and charged hadron fluences, coming from the direct interaction and from backscattering in the calorimeters. The total neutron fluence in the inner detector can be substantially reduced adding a low Z layer near the calorimeter wall. On the forward direction layers of 5 cm of polyethylene will be placed in front of the end-cap calorimeters, and the forward calorimeters will be screened with 20 cm of polyethylene. In the barrel region the low Z material of the TRT offers a satisfactory screening.

Detector component	dose [kGy/yr]	fluence [cm^{-2}/yr]
pixel	34	5.9×10^{13}(a)
		1.6×10^{13}(b)
SCT (barrel)	15	2.7×10^{13}(a)
		1.0×10^{13}(b)
SCT (forward)	10	2.2×10^{13}(a)
		1.6×10^{13}(b)
GaAs	16	1.3×10^{13}
MSGC	7.2	2.0×10^{13}
Barrel TRT	2.5	6.3×10^{13}
End-cap TRT	4.7	1.3×10^{13}
Barrel em calor	0.6	1.5×10^{13}
Barrel tile calor	0.02	1.6×10^{12}
Barrel/EB crack	0.036	2.0×10^{12}
End-cap em calor	53	4.1×10^{14}
End-cap had calor	12	6.1×10^{14}
Forward calor	2300	1.0×10^{16}

Table 1: Maximal yearly values for dose and fluence rates in ATLAS. (a) Total fluence, 1 MeV neutron equivalent; (b) Neutral particle fluence, 1 MeV neutron equivalent.

The damage to silicon detectors due to the 1 MeV neutron equivalent fluences present, can be estimated using the damage functions [2]. The NIEL estimates are precise enough up to 20 MeV of neutrons, but several authors consider [8] that the errors introduced by the damage functions above 20 MeV, as well as for other types of particles can be up to 40%.

The most important problem for silicon is related to the absence of reliable results on pions, particles which dominate the hadron fluence in the innermost layers, close to the beam axis. Some studies on the subject have been produced lately [9, 10], but the problem is still open.

Charged hadrons originating from the interaction point and which produce radiation levels in the inner detector layers have a typical $1/r^2$ dependence (r is the distance to the beam axis). Neutrons

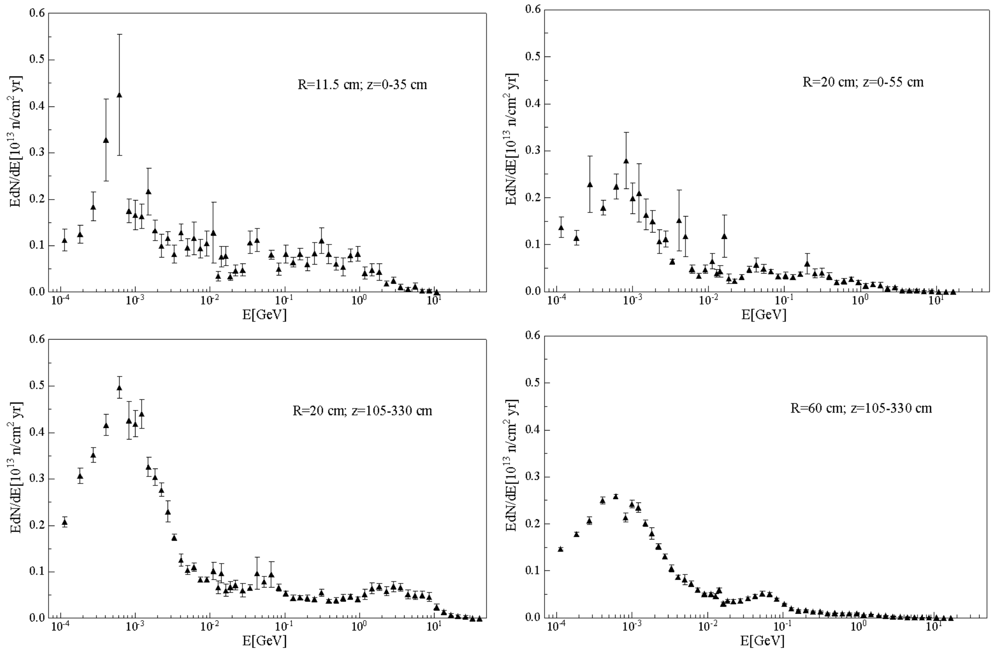

Figure 1: Neutron spectra in ATLAS

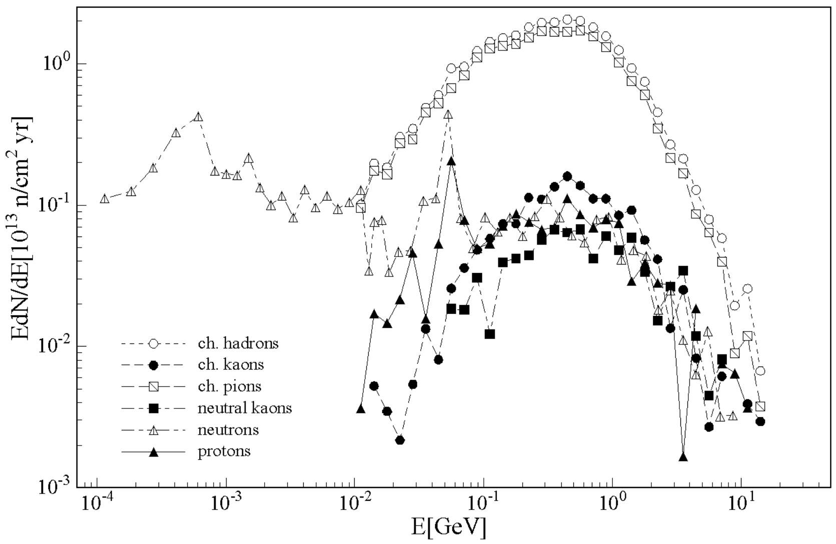

Figure 2: Particle spectra in ATLAS: charged and neutrals

produce a uniform albedo and dominate at large radii.

The radiation levels in other detector components are not of interest in the present study.

Figures 1 and 2 present some spectra calculated by MC simulation for ATLAS in the Cosener's House layout, taken from reference [7].

1.2 The CMS detector

Fluence calculations have been performed for CMS as well in a series of papers [9, 11].

As in ATLAS, we are interested especially in fluxes and spectra in the inner detector.

The neutron albedo and its spectrum depend to a great extent on the composition of the electromagnetic calorimeter. The lead–plastic scintillator option produces a soft albedo, because of the high content in hydrogene of the scintillator. The $PbWO_4$ crystal calorimeter generates an intense neutron albedo with many neutrons with energies above 100 KeV. However a few cm of polyethylene are enough to moderate the neutrons. In the central tracker region we are mostly concerned with the damage to silicon. Here low energy pions are dominant. Above 50 cm, the most important contribution is of neutrons [12].

Neutron fluxes in the central cavity vary in the limits of one order of magnitude around a typical value of 10^{13} n/cm^2 year, while the charged hadron flux decreases from 2.5×10^{14} at r=7.5 cm, to 10^{12} cm^{-2} yr^{-1} at 1 m.

The multiplicity distribution of the neutrons is not flat in η. Supplementary contribution to the neutron flux at high z comes from the beryllium–aluminum pipes at z=1.5 m, and from the albedo given by the forward calorimeter.

Figure 3 presents particle spectra, calculated for the CMS in [11].

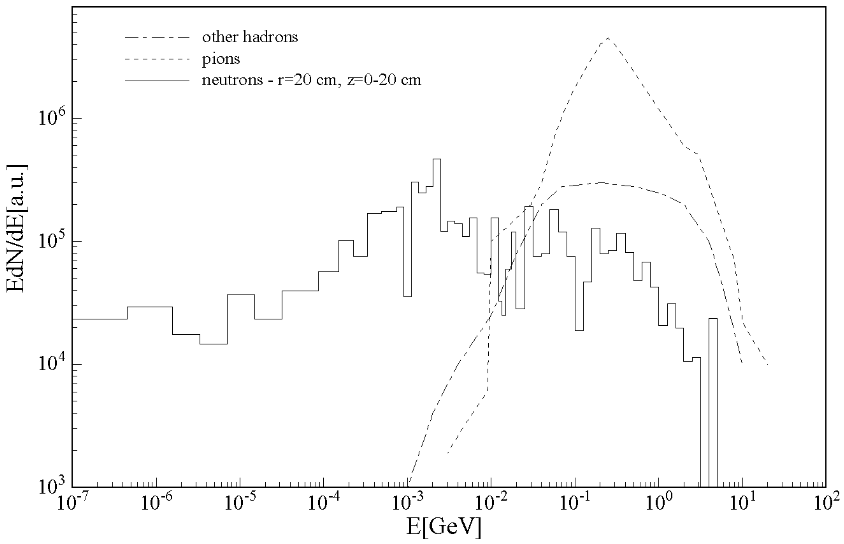

Figure 3: Particle spectra in CMS

2 Radiation fields for hardness studies

Specific sources are used for the radiation hardness studies of the detectors designed for experiments at LHC or other similar high intensity fields (HERA–B or others).

High energy protons are available from the 24 GeV proton pulsed beam at CERN SpS, with a fluence rate of $\sim5\times10^9$ p/cm^{2}s [13]. Some studies have used lower energy protons: 21.1 MeV

(Hamburger Isochron Zyklotron) [14] or 500 MeV at the SATURNE cyclotron in Saclay [15], different beams between 400 and 800 MeV at TRIUMF and LAMPF [16].

Pion tests used the intense π beam at PSI (Paul Scherrer Institute) Villigen, Switzerland ($\Pi - E_1$), with momenta of 100–450 MeV/c. Pions are produced from the collision of a primary accelerated proton beam, obtained from the PSI cyclotron, on a graphite target [17]. The maximum current of the cyclotron is 800 μA. Lepton contamination of the beam is of about 10%. The neutrons associated with the pions have been measured for a π^+ beam: at 5 cm from the beam the contamination with thermal neutrons was 0.3–0.8%, and 0.2–0.5% for fast neutrons. In order to study differences in damage produced by π^+ and π^-, positive pion beams of 65 to 331 MeV, and negative pions of 236 MeV have been obtained at PSI [18].

Most of the tests are made however in neutron fields, because these particles are very abundant in the inner detectors, produce mainly bulk damage similar to other hadrons, but also because these sources are more accessible and the exposures less expensive compared to protons or pions. Uniformity of the field is also easier to achieve on larger areas. The results can be correlated between different types of particles in the NIEL scaling hypothesis, using only a few beam tests. The proton and the neutron differ from the point of view of radiation damage only by the charge of the proton, and its capability to produce ionization, and of course by specific nuclear reactions. In principle these differences are taken into account in the scaling function (damage function).

Neutron sources used in testing are very different. Some are monoenergetic, or with a narrow spectrum, based on nuclear reactions, like: ^{3}H(p,n)^{3}He, ^{2}H(d,n)^{3}He, ^{3}H(d,n)^{4}He, ^{9}Be(d,n)^{10}B, ^{7}Li(p,n)^{7}Be. Others are beams coming from nuclear reactors: directly, as in the case of the fast, pulsed reactor at JINR Dubna, IBR–2, or indirectly: the INPE (Institute of Nuclear Physics and Engineering, Bucharest, Romania) $\Sigma\Sigma$ facility, a thermal-fast coupled device. A third category are spallation sources, connected to high energy acelerator beams bombarding thick targets (blocks) in which the neutron spectra are typically wide (the ISIS facility at Rutherford Appleton Laboratory, or PSAIF[3] at CERN).

A special category, rarely used because of low intensities, are the isotopic sources, like e.g. the ^{252}Cf or Am-Be fission sources.

In the following a presentation of the main features and spectra of the more frequently used neutron sources for radiation hardness studies will be given. The value for the hardness parameter will also be given for all the spectra, a specific parameter in silicon damage studies used as a scaling factor in the NIEL hypothesis. This parameter will be defined and thoroughly discussed in [2].

2.1 Monoenergetic neutrons

In the introduction to this section, the monoenergetic and narrow spectra neutron sources for damage studies have been enumerated.

Before starting the description of these sources a remark should be done: the collimated Be(d,n) at PTB (Physikalisch-Technische Bundesanstalt Braunschweig) has a quite wide spectrum, so its presentation as a monoenergetic beam is somehow not correct, The Li(p,n) source at the Lowell University, Massachussetts, U.S.A., is also not exactly a monoenergetic source. But all the sources presented here have a few common features: the neutron beam results from a nuclear reaction on a target, and the spectra are definitely narrower than those obtained at reactors or at spallation sources.

The monoenergetic fields at PTB are characterised by very low scattered radiation levels. They are obtained by bombarding thin, air-cooled targets of Ti-^{3}H or Ti-^{2}H, with accelerated deuteron or proton beams. The reactions used are well-known as to their spectra and fluences [19].

2.1.1 The 1.2 MeV T(p,n) source at PTB

The 1.2 MeV neutron beam is obtained from the ^{3}H(p,n)^{3}He reaction. The target is a vacuum evaporated titanium layer on a silver disk 1 mm thick, which should stop the 2.03 MeV protons at the rear side if the target. The titanium layer contains adsorbed tritium.

[3] PS–ACOL Irradiation Facility, at CERN's proton synchrotron in Geneva

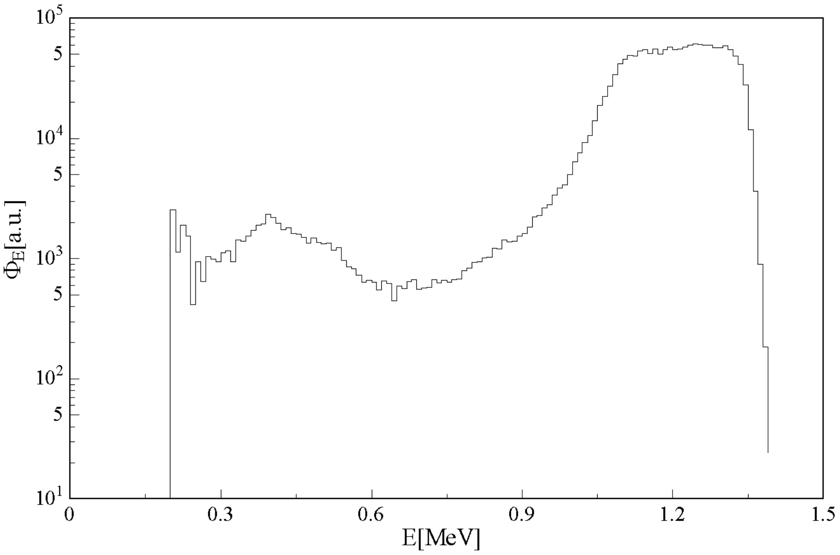

Figure 4: The spectrum of the 1.2 MeV T(p,n) source at PTB

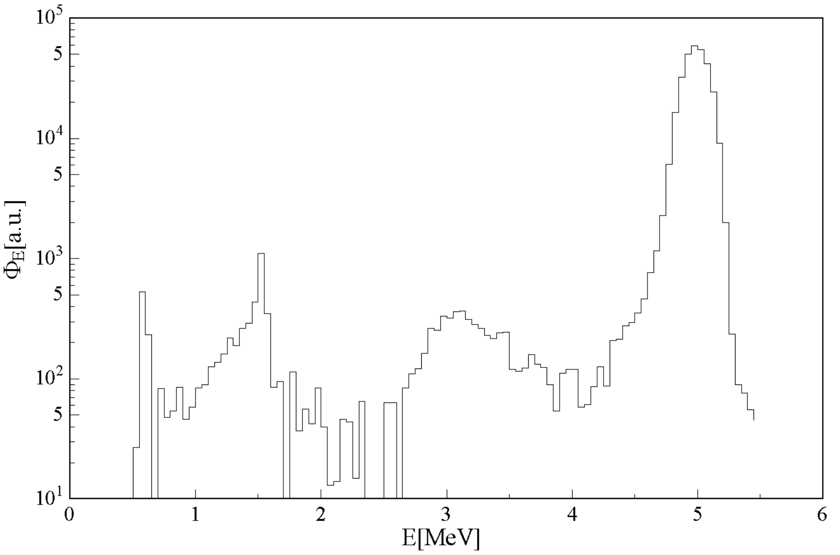

Figure 5: The spectrum of the 5 MeV D(d,n) source at PTB

The spectrum of this source, measured by time of flight technique at 3 m from the target and at 0^0 to the proton beam axis, is given in figure 4. A proton recoil proportional counter was used for fluence measurements. Supplementary monitoring was achieved by using a plastic scintillator [19].

The hardness parameter for this spectrum in [19] is 0.88. The value obtained in this work is: (0.86±0.03), calculated with the folding method described in [2].

2.1.2 The 5 MeV D(d,n) source at PTB

The deuteron beam used to obtain the 5 MeV neutrons on a similar Ti-Ag target, doped with deuterium, has an energy of 1.86 MeV. The reaction used is $^2H(d,n)^3He$.

The spectrum has a pronounced peak at 5 MeV containing 95.8% of the total neutron fluence. The rest of 4.2% of fluence covers the energy range between 0.5 and 4.5 MeV.

The spectrum in figure 5 was measured by time of flight technique at 5 m from the target, at 0^0 to the deuteron beam axis. A proton recoil telescope was used for fluence measurements and supplementary monitoring was done by means of a plastic scintillator [19].

The hardness parameter for this spectrum given in [19] is 1.60, corresponding to 5 MeV. The value calculated on the spectrum in this work is (1.68±0.03) [2].

2.1.3 The 14.1 MeV T(d,n) source at UKE

The 14.1 MeV spectrum is obtained at a therapy neutron source at the University Hospital Hamburg-Eppendorf (UKE – Universitätskrankenhaus Eppendorf). In this case, a 500 keV atomic deuteron beam is incident on a rotating tritium target. The source is collimated for its therapeutical use, but the collimator can be partly removed in the detector tests, in order to obtain higher rates at distances between 10–60 cm.

The spectrum was measured in air, at 100 cm from the target, using a scintillator detector NE213 [20]. It was obtained with an unfolding method, using the response matrix of the plastic scintillator counter [19].

This spectrum is given in figure 6.

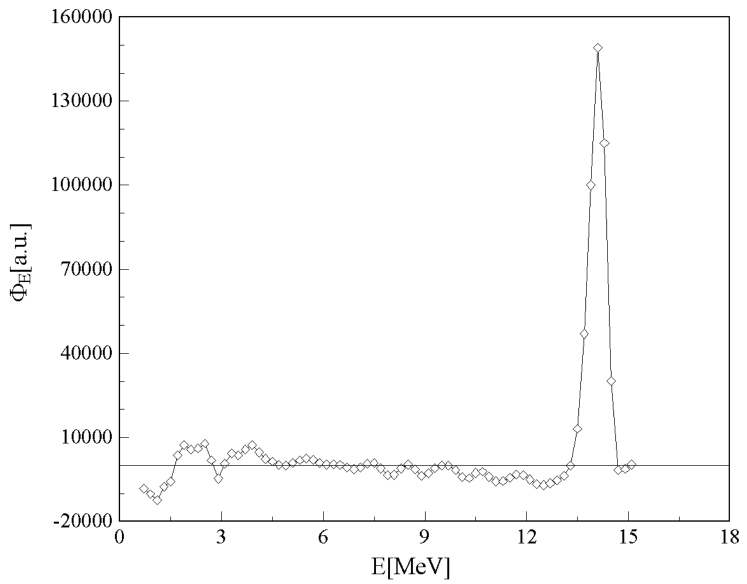

Figure 6: The 14 MeV T(d,n) spectrum at UKE

The hardness parameter of the UKE T(d,n) source is 1.88 [19]. The folding on the peak gives κ=(1.93±0.06) and <E>=14.1 MeV [2].

2.1.4 The Be(d,n) source at PTB

The ^{9}Be(d,n)^{10}B source at PTB [21] is a very intense neutron source. The accelerated deuterons obtained from the PTB cyclotron have energies up to 13.5 MeV and the currents are of about 30 μA. The rear side of the Be target is cooled with water, and the front side is connected to the beam pipe. The maximum power consumption is 500 W. The collimator is a multilayer structure, containing Fe, polyethylene with boron carbide, Pb and W, which assures an adequate beam for neutron therapy, a possible application of this source. Part of this collimator can be removed during the detector irradiations.

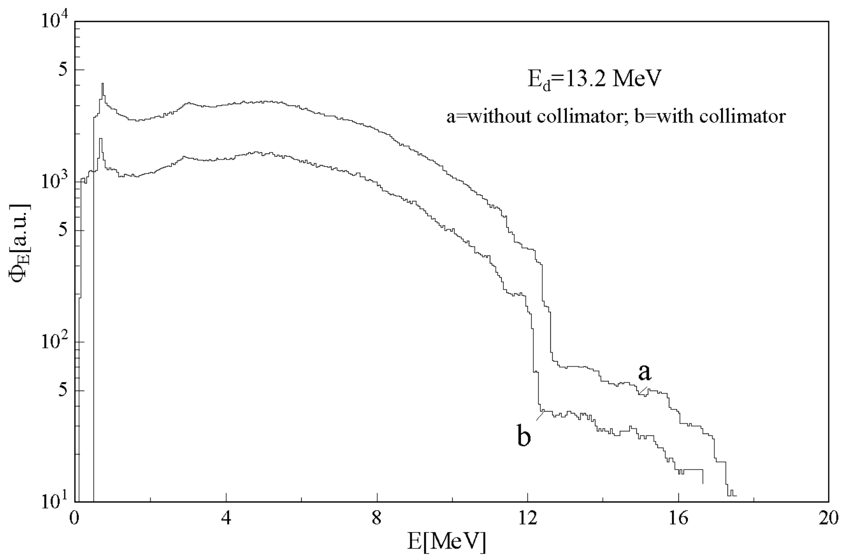

Figure 7: The Be(d,n) PTB source with an average energy of 5.2 MeV

The intensity of the beam is monitored with a transmission ionization chamber situated at 90^0 to the collimated neutron beam. The energy of the deuteron beam is known within an error of $\pm$20 keV. The spectrum, measured by time of flight technique, at 80 cm from the target and at 0^0, is given in figure 7 [19].

The average energy of the spectrum is about 5.2 MeV, and the hardness parameter 1.53 [19]. The value calculated in this work is (1.46$\pm$0.03) [2].

2.1.5 The Li(p,n) source at Lowell

This source uses a proton beam from the 5.5 MeV van de Graaff accelerator at Lowell University in Massachussetts, and a metallic Li target [22]. The Lowell Li(p,n) source is characterised by simple dosimetry, based on measurement of γs emitted by ^{7}Be, small number of associated γs, typically one 422 keV quantum to 20 fast neutrons and practically, neutrons with energies below 10 keV are missing in the spectrum, the ratio between slow and fast neutrons is less than 0.1%.

For detector and integrated circuit damage studies, protons of 4 and 5 MeV have been used. At an intensity of 25 μA, in an hour one can get a fluence of 4×10^{12} n/cm^2.

The schematic of the nuclear reactions and the decay of the reaction products is given in figure 8.

Analysing the decay schematic of ^{8}Be we see that the number of neutrons produced is equal to the number of ^{7}Be nuclei. This is a radionuclide with a half-life of $T_{1/2}$=53 d, producing 10.4% ^{7}Li on the first excited state, of 478 keV. Measuring the de-excitation gamma rays, the neutron fluence can be easily deduced. The neutron spectrum at this source has been determined from calculations, backed with time of flight spectrometry [22]. The spectrum obtained is presented in figure 9.

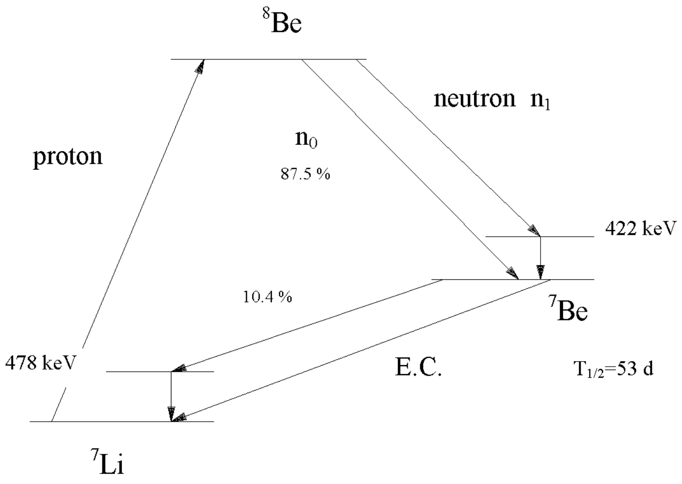

Figure 8: Schematic of principal reactions in the Li(p,n) source

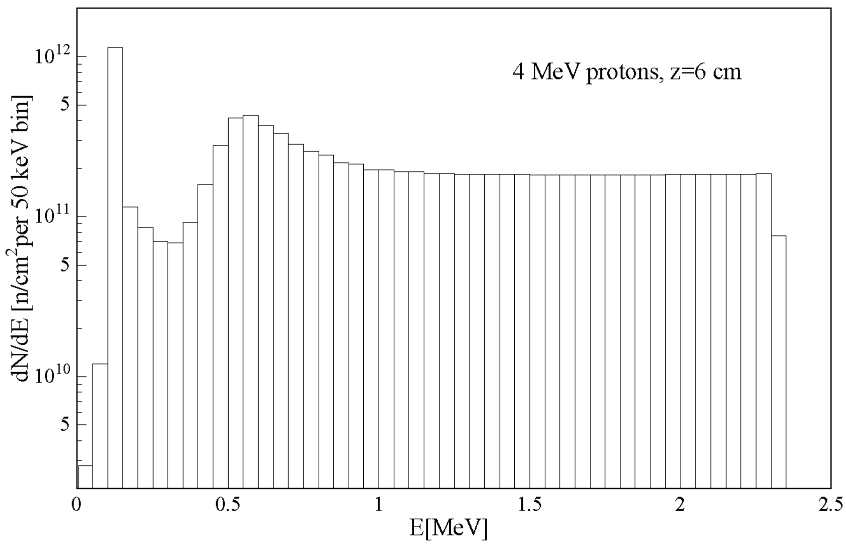

Figure 9: The Li(p,n) source spectrum at Lowell

No published result on the hardness parameter for this source is available in literature[4]. As a result of the work reported here the hardness parameter for this source is 0.90 [2].

2.2 Fission and isotopic sources

This category is represented by nuclear reactors and sources based on beams obtained at reactors, like the $\Sigma\Sigma$ facility, and isotopic sources, like ^{252}Cf, Am-Be, Pu-Be.

The IBR–2 source at JINR Dubna and the $\Sigma\Sigma$ facility will be described in more detail, as they have been used in the experimental part of [1]. The other sources are only enumerated.

2.2.1 The IBR–2 reactor source

The neutron beam used for radiation damage studies at JINR Dubna comes from the fast pulsed reactor IBR–2 at the Laboratory for Neutron Physics. An extension in channel 11 of the reactor, belonging to the Activation Analyses Group has been used for hardness testing.

The flux density at the irradiation position, situated at 720 cm from the reactor core, is approximately 3×10^8 n cm^{-2} s-1. The useful transverse area, with good uniformity, is about (15×20) cm^2. The beam can be cut off with a shutter, when the necessary fluence has been accumulated. Possibilities for filtering are available to modify the shape of the neutron spectrum, e.g. boron carbide.

Fluence is monitored with activation foils of Ni, with an overall uncertainty of $\sim$5%.

The spectrum at IBR–2 is presented in figure 10. It is close to the fission spectrum.

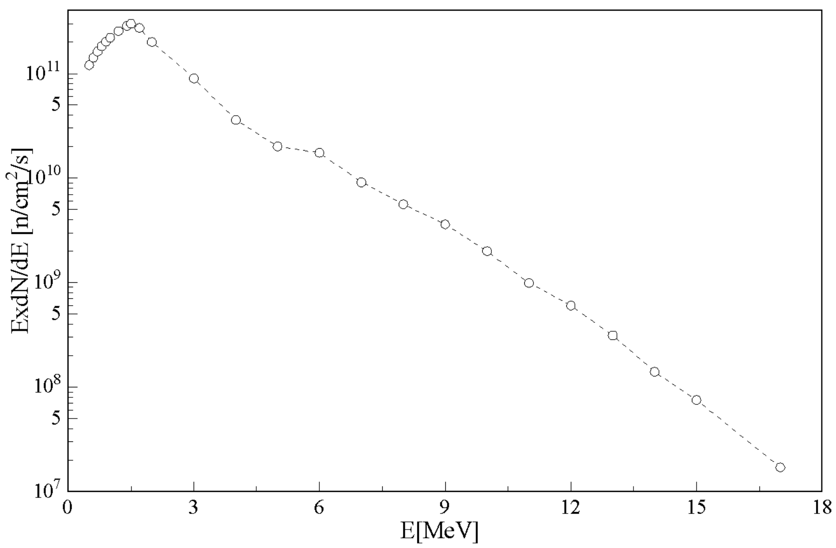

Figure 10: The spectrum of the IBR-2 at JINR Dubna

The uncertainty of the spectrum measurement has been determined in a series of intercomparisons, and it is $\pm$15% [23]. Unfortunately there are no available published data on this source, the information presented is based on private communications[5].

Though it was not possible either to represent it graphically, or to take it into account in the calculations, this spectrum extends to energies below the 0.5 MeV limit of the tabulated data.

The gamma dose/neutron fluence ratio is A=5.6×10^{-11} Gy n^{-1} cm^2 [23]. The hardness parameter, calculated on the spectrum in figure 10 is 1.05 [2].

[4]The fluences at each irradiation are given in 1 MeV equivalent neutron fluence, using the old ASTM damage function. For a detailed discussion, see [2].

[5]See reference in [23].

The temperature in the irradiation channel at IBR–2 is 15^0C.

2.2.2 The ΣΣ irradiation facility

The ΣΣ facility is an intermediate neutron secondary standard source for reactor dosimetry and radiation metrology. It is a uranium multishell spherical source situated in the graphite thermal column of the VVR–S research reactor at INPE Bucharest – Măgurele. It is a thermal – fast neutron convertor [24, 25].

The fission source is a natural uranium multishell sphere, with a central cavity. The outer diameter is 245 mm, the inner 110 mm. The inner wall of the sphere is covered by a 17.5 mm vibrocompacted aluminum plated boron carbide screen. The system has two instrumentation channels (one horizontal and one vertical), which can be shut with uranium plugs. The graphite block has corresponding instrumentation channels.

The configuration of the system is identical to the ΣΣ – Mol sphere (Belgium).

The spherical uranium shell converts the thermal flux in fission acts. The resulting neutrons are scattered elastically and inelastically in the uranium. The boron carbide screen absorbs thermal and epithermal neutrons.

The neutron spectrum has been measured by proton recoil spectrometry with H_2 and CH_4, at different pressure, for the energy range of 10 keV – 1.4 MeV, and with fission chambers and activation foils. The method of calculation and unfolding of the spectrum uses the SAND II code[6], the ANISN spectrum and cross sections from the ENDF/B–V compilation [26].

Intercomparison with the activation foil spectrometry between the ΣΣ sources at INPE and MOL – Belgium showed a very good concordance of the results. The part of the spectrum below 6 keV is less precisely known. The maximum uncertainty estimated was 3.5%.

The average energy of the spectrum is 0.82 MeV, and for the energy range of 10 keV–18 MeV, at nominal power, the integral flux density is 3.385×10^9 n/cm^2 s. The spectral index for the ΣΣ sphere is (17.2±0.7) [24], and the hardness parameter 0.663 [2].

The spectrum of the ΣΣ source is given in figure 11.

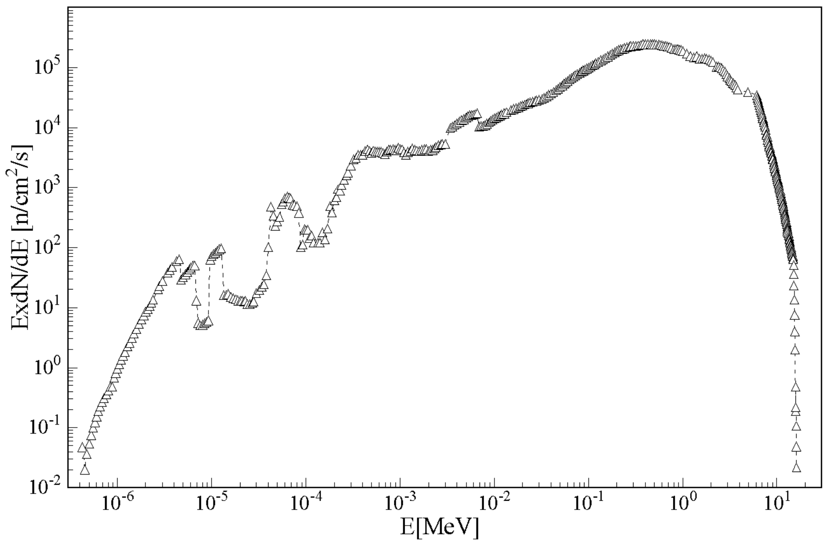

Figure 11: The ΣΣ spectrum at the VVR–S reactor at INPE

The spatial distribution of the neutrons in the sphere has been measured with miniature cylindrical

[6] See references in [24].

fission chambers. The nonuniformity of the field along the thermal column axis is 2.5%, and 6% in the horizontal plane, along the axis, from the center to the outer limits. The gradient of the fission rate along the horizontal axis is related to the thermal flux gradient, but the differences are attenuated by multiple scattering of the intermediate neutrons in the sphere.

The temperature during irradiation in the ΣΣ sphere increases with fluence, which is important for the silicon detector irradiations. Up to fluences of the order of 3×10^{12} n/cm^2, temperature increases to 22–23^0 C, between 10^{13}–10^{14} n/cm^2: 25–30^0 C, and for 10^{14}–10^{15}n/cm^2, it increases further to 33–35^0 C [23].

An important aspect to be considered in the irradiation tests is the gamma background.

The fission of uranium produces prompt gammas of 6–8 MeV. The fission products themselves are radioactive. Measurements in the mixed n–γ fields have to been done with special precautions and preliminary calibrations. For reference see [27, 28].

The ΣΣ facility is the source with the smallest gamma background associated to high neutron fluences, compared to the irradiation facilities used for radiation hardness studies of silicon detectors. Its spectrum is best known among the wide neutron spectra. Being a metrological secondary standard its spectrum is especially precisely known, comparable only with the standard sources at PTB. The ΣΣ facility has the disadvantage of the impossibility of controlling the temperature during irradiation, the restricted volume which can be used for the samples to be irradiated does not allow the cooling of the samples.

2.2.3 Other fast neutron sources

It is common practice in reactor dosimetry to use the spectral index SI to compare fast neutron sources. The definition for SI is:

$$SI = \frac{\Phi(E_n > 10keV)}{\Phi(E_n > 3MeV)} \tag{1}$$

This index gives information of the low energy neutron contents in the total spectrum.

Table 2 lists a series of fast neutron beams with their SI values and the corresponding hardness parameter κ.

Source	type	SI	κ	references
FBR	A	7.9	0.92	[24]
SPR	A	8.4	0.88	[24]
APRF	A	8.3	0.90	[24]
ACRR	B	16.8	0.64	[24]
TRIGA	B	8.40	0.79	[24]
ΣΣ	fission U	17.2	0.66	[2, 24]
IBR–2	A	11.7	0.9–1.05	[2, 23]
^{252}Cf	B	4.2	1.06	[24]
Cf–D_2O	–	7.59	0.55	[24]
Am-Be or Pu–Be	–	–	1.42	[14]

Table 2: Comparative spectral index and hardness parameter values for different fast neutron sources; Type (A) are fast reactors, and (B) moderate fission fields. FBR= Fast Burst Reactor, SPR=Sandia Pulsed Reactor, APRF= Aberdeen Pulsed Reactor Facility, ACRR= Annular Core Research Reactor, TRIGA= Rotating in core irradiation facility.

Comparing the IBR–2 values with the tabulated fast reactors, we have to mention that probably the actual values for the parameters of interest should be close to those from the other similar facilities, and the difference of about 15% in κ is due to the artificial energy cut at 0.5 MeV.

2.3 Spallation sources

Spallation sources use high energy beams, which by absorption in a material produce very wide neutron spectra. By the mode of particle production, they simulate the best the detectors at the collider, but one should have clearly in mind the difference in maximum available energy, which is much different, as the contents and volumes of the blocks of matter as well.

The spectra of the ISIS source at Rutherford Appleton Laboratory and of PSAIF at CERN have been both measured by the activation technique, and the spectra have been calculated with the same unfolding code LOUHI.

The output of the program is:

- the neutron spectrum in n/cm^2/s/MeV and logarithmic bin (FL/BN/LG) in 40 logarithmically equally spaced steps on the energy scale (the energy range for the two sources considered is 10^{-8} to 1400 MeV);
- the total flux integrated on the spectrum;
- The neutron fraction above a certain value of the energy, in percents;
- the measured and calculated value of the integral $I = \int_0^\infty \Phi(E)\sigma(E)dE$ for each activation reaction, and their ratios. (This gives an indication on the fit quality.)

2.3.1 ISIS

The ISIS facility at RAL [29] is constructed of a graphite block, covered with copper, mounted in the beam, between the injection and extraction sites from the 800 MeV proton synchrotron at RAL. This element is used as a collector for the protons coming from the injector and which are not captured by the RF wave in the accelerating phase. The injection is at 70 MeV, and the extraction at about 800 MeV. The 70 MeV protons are very abundant and they produce the majority of the spallation

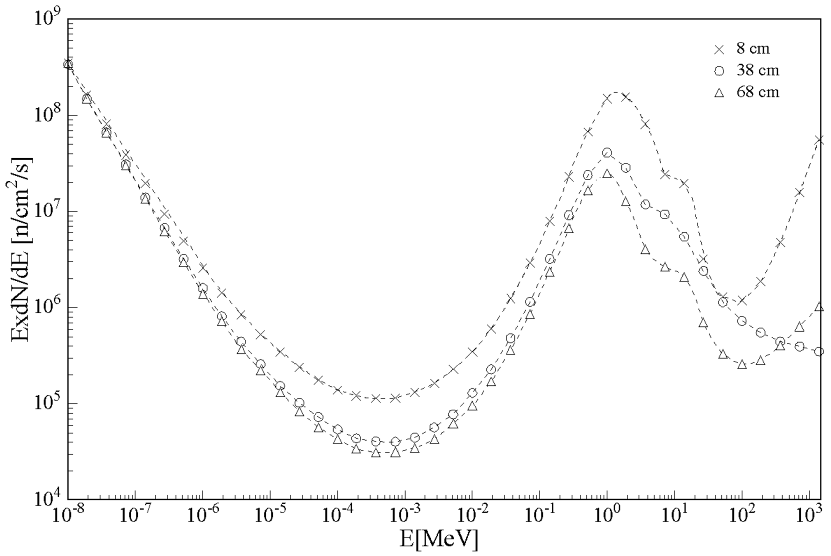

Figure 12: Spectrum for the ISIS spallation source at RAL

processes generating neutrons. During acceleration and at extraction, the proton losses are smaller. The value of 800 MeV is a clear kinematical limit, which will be referred to in [2] — no neutrons can be produced above this limit.

The area above the collector is free and allows mounting a light frame with three irradiation positions, at 8 cm, 38 cm and 68 cm. The access to it is limited to very short times or at closing down the accelerator.

The neutron spectra, calculated for ISIS in the three irradiation positions are shown in figure 12.

The characterization of this source regarding the hardness parameter has been associated with some problems, connected mostly to the incorrect interpretation of the output from LOUHI and the choice of the integration limits — this discussion was presented in [2]. The average value for κ at ISIS is 1.0±5% [2].

2.3.2 PSAIF

The neutron irradiation facility at CERN, the PSAIF (PS= Proton Synchrotron, A= ACOL =Antiproton COLlector, I= Irradiation, F=Facility) has been built in 1990, and is situated near the antiproton target at $Sp\bar{p}S$. The antiproton target is made of iridium and it is bombarded by a 26 GeV proton beam coming from the proton synchrotron [30]. The field in this region has high levels of dose and fluence, determined by secondary high energy particles, typical in accelerator environment. The irradiation site is in a cylindric pipe, above the beam line, upstream the beam dump. The field contains except the large number of neutrons, some protons and pions. The presence of protons has not been noticed during the spectrum measurements. No results are available on pion levels or spectra.

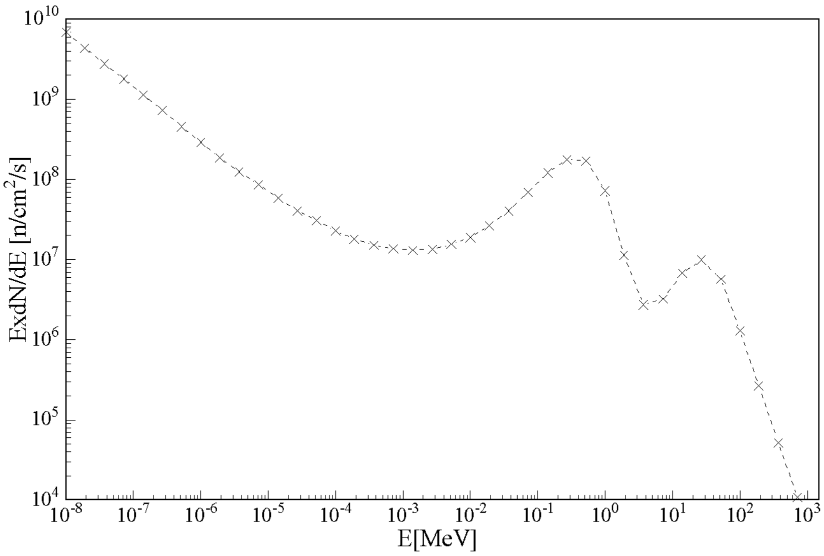

Figure 13: Neutron spectrum at PSAIF at CERN. The energy cut at 140 keV has no justification

The neutron spectrum at PSAIF measured with activation technique and calculated with the LOUHI unfolding code is shown in figure 13.

This irradiation facility is the most questionable with respect to its spectrum and reproducibility. The low energy neutron part is very high and it is even possible that it is however an underestimate [30]. At the time of the spectrum measurements the low energy part was not treated with special attention, as it was considered that low energy neutrons do not create significant damage in silicon.

New measurement would be more than welcome.

The calculation of the hardness parameter for PSAIF is a real problem. κ changes continuously with the different energy cuts in the spectrum integrals. The complete discussion is given in [2]. For the currently used artificial low energy cut used in the radiation hardness tests (140 keV), the hardness parameter obtained in this work is (0.74±0.04) [2].

2.4 Summary on the properties of neutron irradiation facilities

The main characteristics of the neutron irradiation facilities used for damage studies are given in table 3. For a detailed discussion of the hardness parameter and other values, see [2].

Source	<E> [MeV]	$d\Phi/dt$[n/cm^{2}s^{-1}]	κ^a	κ^b
ΣΣ	0.82	3.385×10^9	0.663	0.66–0.70
PSAIF	0.062	1.23×10^{10}	0.025	
elastic thresh.	1.32	5.81×10^8	0.502	
140 keV	1.99	3.19×10^8	$(0.78\pm0.04)^c$	$\sim$ 1–1.08
ISIS^d			1.00 ± 0.05	1.02–1.5
Lowell	1.06	1.1×10^9	0.90	
T(p,n)^{3}He	1.2	10^7	0.86 ± 0.03	0.88
IBR–2	1.60	3×10^8	0.9–1.05	1.05
Be(d,n)B	5.2	5×10^8	1.46 ± 0.03	1.53
D(d,n)^{3}He	5	1.5×10^7	1.68 ± 0.03	1.60
T(d,n)^{4}He	14.1	6×10^8	1.93 ± 0.06	1.88

Table 3: Main characteristics of neutron irradiation facilities used or damage studies of silicon detectors. (^{a})= κ from [2]; (^{b})=κ in literature; (^{c})= $\kappa^\dagger$ [2]; (^{d})= average value for the three geometries, with spline interpolation and high cut at 720 MeV (it makes no sense to define an average for the flux density or for the average energy, as the values given are for the three different spectra)

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