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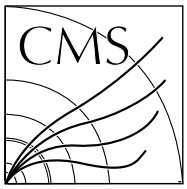

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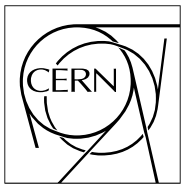

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Neutron flux Measurement at Tapiro fast reactor for APD's Irradiation fluence evaluation

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Abstract

The Avalanche Photodiodes (APD) were chosen as photon sensors for the barrel region of the CMS electromagnetic calorimeter. The LHC will be a hard environment for what concerns the radiation levels in the detectors. The most relevant damage on APDs is caused by neutrons that produce an increase in the dark current of these devices.

In the CMS-ECAL collaboration a big effort was indeed done to understand this damage, but the evaluation of the absolute effect was limited by the knowledge of the neutron flux calibration of the various irradiation facilities.

This investigation describes the calibration of the neutron flux of the Tapiro reactor in Rome and the calculation of the Non-Ionizing-Energy-Loss on Silicon for this reactor.
The damage parameter α for the APDs is evaluated to be about $10 - 11 \cdot 10^{-17}$ A/cm/neutron at 18^{o}C and 2 days after the irradiation.
Some cross-checks with other irradiation facilities are also presented.

Introduction

The Avalanche Photodiodes (APD) have been chosen as photon sensors for the scintillating crystals of the CMS electromagnetic calorimeter in the barrel region [1]. The prototypes which are nowadays available have been optimized for radiation hardness in order to survive the neutron fluence expected in ten years of operation of the detector in LHC.

In order to study the damage on the APDs, several prototypes have been irradiated in the various irradiation facilities available for the CMS-ECAL collaboration. To compare the results a good absolute calibration of the dose is mandatory. Furthermore, as the neutron damage on silicon devices depends on the neutron energy, a detailed knowledge of the neutron spectrum of each source is fundamental for this type of measurements.

The neutron source used by our group is the TAPIRO reactor at ENEA-Casaccia near Rome.

This note is divided in two parts. The first part describes the TAPIRO reactor calibration performed with two different methods. The second part shortly reviews the neutron damage on silicon devices and exploits the calculation of the Non-Ionizing-Energy-Loss relative to 1 MeV neutrons for silicon in different irradiation positions in the TAPIRO. Then the measurements done on the APDs with this reactor are described. In particular the results obtained during an APD irradiation performed simultaneously to the reactor calibration are discussed. Finally some cross-checks done with other sources are described.

All this work is finalized to a precise and reliable evaluation of the damage parameter α of neutrons on APDs.

Contents

Part I

Neutron flux calibration in the TAPIRO Reactor

1 The High Enriched ^{235}U Copper Reflected TAPIRO Reactor

The TAPIRO reactor [2] is a high enriched Uranium-235 copper reflected fast neutron source.

The reactor started up on 1971 and during its operational life has performed thousands of irradiations in fields which span from nuclear physics to biological application including damage studies.

The TAPIRO reactor core is a cylinder of 6.20 cm radius and 10.87 cm height. The fuel is a metal alloy (U 98.5%, Mo 1.5%), with a fully enriched ^{235}U (93.5%). The critical mass is 21.46 kg. The maximum nominal power is 5 kW thermal while the maximum neutron flux at the core centre is $2.2{\cdot}10^{12}$ n/cm^2/s. The copper reflector (of cylindrical shape, 72 cm height) is divided into two zones : the inner zone up to 17.4 cm radius and the outer zone up to 40 cm radius. The copper reflector is surrounded by the biological borate concrete shield (170 cm thick) hosting a thermal column cave (Fig. 1) which can be filled with concrete or graphite blocks. The copper reflector inner zone contains the control rods (Fig. 2). A sector of 60^o of the copper outer reflector zone can be replaced by absorbing and/or fissile materials in order to modify the outgoing neutron spectrum toward the thermal column cave.

The thermal column cave is a very interesting facility which can be used for shielding and/or sub-critical assemblies studies as well as for locating apparatus to be irradiated. The maximum dimensions available for the cave are 110×110 cm$^2\times160$ cm (length). The experimental configurations are mounted on a trolley.

As it is shown in Fig. 1 and 2 a number of channels, of different dimensions, cross the reactor reflector and shield. These channels are able to host activation foils as well as small biological samples, rats, detectors of various type and size etc. One of these channels (the diametral channel) crosses the reactor core midplane allowing to locate foils and samples of 8 mm diameter inside the core. It was demonstrated [3] that the neutron spectrum at the TAPIRO core centre is very close to that of ^{235}U thermal neutron induced fission neutron spectrum.

The other experimental channels do not reach the core but are located at different distances from it, allowing for a large number of different neutron spectra to be available. In the past years a big effort was devoted to the neutron characterization of the TAPIRO reactor and the results are reported in Ref. [3–5] and references therein, in the following called "*reference calibration*".

2 Neutron Flux Measurement

In order to analyse the APD results, it is necessary to precisely know the neutron fluence to which they were irradiated. This requires a good knowledge of the neutron flux in the experimental position.

For the purpose of the APD's irradiation the so called Radial-1 channel (Fig. 2) was used for most of the irradiations.

Two different approaches were used to measure the total neutron flux spectrum.

- The first is based on the irradiation, in the experimental position, of a number of activation foils from which, by unfolding methods, both the neutron flux shape and its integrated values are obtained.
- The second method is based on the irradiation of ^{235}U fission foils both in the core centre and in the experimental position, contemporary to APD's irradiation.

The first method was used to calibrate also the RAL flux as described in [6].

The second method allows to get the total neutron flux in the Radial-1 channel by comparison to that in the core centre and was necessary because the APDs' irradiation were performed with a modified configuration of the TAPIRO reactor, so the results obtained from the unfolding method cannot be directly compared with the results reported in [3] and needed to be validated by an independent method.

The two major modification of the TAPIRO reactor with respect to the reference configuration are the increase of the core critical mass by about 100 g of metallic ^{235}U and the substitution of the 60^o movable sector of the copper outer reflector by an outer reflector made of an Aluminium alloy.

3 The Unfolding Method

The unfolding method is based on the calculation of the neutron spectrum by means of an iterative method. Neutron energy spectra are determined by an analysis of experimental activation detector data.

3.1 The SAND-2 Code

For the analysis of the activation foils the unfolding code SAND-2 was used [7]. The procedure starts with a given flux spectrum which is used as initial guess for the solution. This spectrum is multiplied by the cross-sections to get the calculated reaction rates (RC). The RC data are compared with the experimental reaction rates (RE). From the calculated RC/RE ratio a weighting function (of energy) is obtained for each foil, based on the sensitivity function (differential cross section multiplied by the differential flux) for that foil calculated at the current iteration. The foil weighting functions are applied to an averaging procedure to obtain an average correction factor at each energy, based on the RC/RE ratio for each foil and upon the relative contribution of the flux at the given energy to the activity of that foil. The average correction factor is thus applied to the current evaluated flux value at each energy, to obtain the next iterative flux spectrum. The evaluated neutron flux spectrum is presented in a tabular form of 640 energy groups from 1.0E-10 MeV up to 20 MeV.

3.2 Activation Measurements and Results

To unfold the TAPIRO reactor flux spectrum in the Radial-1 channel, the activation foils and reactions listed in Table 1 were used. They cover the whole energy range of interest for the reactor. The used foils were 0.8 cm or 1.2 cm diameter and 0.01 cm thick. The Gold and Manganese foils make exception since, to avoid self-shielding effects, Al/Au (at 1% Au) and Mn/Al (at 5% Mn) alloys were used. The irradiation period lasted 1200 s and the irradiation power was at the nominal level of 100 W.

Activation foils were measured using HPGe detectors absolutely calibrated. The measurement procedure is briefly summarized in Appendix A.
The measured reaction rates (in unit of reaction/atom/second) are reported in Table 1 together with the quoted uncertainty. The overall contribution to the uncertainty comes from the absolute calibration of the germanium detector ($\pm$2.0%) and the peak area.

As far as the nuclear data (half-lives, abundance etc.) are concerned, data from [8] were used.

Inserting the measured reaction rates in the SAND-2 code the unfolded flux spectrum shown in Fig. 3 was obtained. The total flux was calculated to be:

$$\Phi_{\mathrm{RC}} = 3.7 \cdot 10^{10} \mathrm{n/cm^2/s} \quad \text{at 100 W.} \tag{1}$$

As input guess spectrum a 25 energy group spectrum obtained from discrete ordinate calculation [9] using DOT-3.5 code [10] was used. The upper energy tail of the spectrum was assumed to be that of a ^{235}U thermal neutron induced spectrum, while the low energy tail was assumed to be a thermal spectrum. Changing the last one with a 1/E spectrum did not change to an appreciable level ($<$10%) the results. The iteration procedure was stopped when the RC/RE ratio was $<$1.05.

The integral flux found in the Radial-1 channel resulted about *twice* the one expected on the basis of the characterisation campaign [3] performed using the "reference" condition for the TAPIRO reactor. This difference can be ascribed to the modification of the reactor configuration, nevertheless a further investigation was performed and will be described in the next section.

In Fig. 3 the calculated neutron spectrum (normalized to 1) in the Radial-1 channel is compared with the neutron spectrum at the core centre unfolded using the data from [3] (the so called "reference" configuration). The measured reaction rates in the core centre are reported in Table 2. The total flux obtained with unfolding at the core centre (normalized to a nominal power of 5 kW) is:

$$\Phi_{\mathrm{DC}} = 2.38 \cdot 10^{12} \mathrm{n/cm^2/s} \quad \text{at 5 kW} \tag{2}$$

to be compared with the value reported in [3], still for the same "reference" configuration:

$$\Phi_{\mathrm{DC}}^{\mathrm{ref}} = 2.2\ (\pm 3\%) \cdot 10^{12} \mathrm{n/cm^2/s} \quad \text{at 5 kW.} \tag{3}$$

This comparison gives some insight about the reliability of the unfolding method at least at the TAPIRO core centre. The unfolding method gives the flux at about 15% precision.

4 The ^{235}U Fission Rate Method

4.1 Need for ^{235}U Fission Rate Measurement

In reactor dosimetry it is assumed that fission reaction rates, like the one of ^{235}U, are integral responses. Basically, the ^{235}U(n,f) rate, divided by the fission cross section, gives the total flux. It is thus possible to get the total neutron flux in the core centre of the TAPIRO reactor, with good approximation, directly by the ^{235}U(n,f) reaction rate measurement, provided that the cross section is known. We recall that it was demonstrated [3] that the TAPIRO core centre has a neutron spectrum very close (deviations arise above 7 MeV where the neutron flux has very low intensity) to that of thermal neutrons induced fission in ^{235}U, thus the ^{235}U fission cross section at the core centre is well known. The evaluated fission cross section for ^{235}U(n,f) in the TAPIRO core centre [9] was 1.27 barn, to be compared with that measured [11] in a thermal neutron induced ^{235}U fission spectrum, which is 1.20 barn. The difference is within $\pm$5%.

The TAPIRO core centre spectrum is not influenced by the recent reactor modifications, so the flux level measurement inside the core by mean of fissile foil, contemporary to an APD's irradiation, should solve the question wether or not the unfolding method is reliable. The results of the APDs irradiation will be discussed in Section 8.

A foil of ^{235}U was also irradiated in the Radial-1 channel together with an APD to check the discrepancy of a factor 2 found for the total flux between the "*reference*" configuration and the unfolding described in Section 3.2.

A third ^{235}U foil was located (together with an APD) at the interface between the Aluminium movable outer reflector and the thermal column cave. This position is of interest since the wider housing is suitable for tests with a large amount of samples.

4.2 The ^{235}U Fission Foils Measurement and Results

The ^{235}U metallic foils used were 0.01 cm thick, the ^{235}U was enriched at 93.5% while a small amount of ^{238}U (5.85 %) was present. The irradiation lasted 1320 sec at the nominal power of 100 W. The γ-ray line at 1596.17 keV of Ba-La-140 fission product was used. To perform the measurement it ought to account for the radioactive equilibrium between ^{140}Ba ($T_{1/2} = 12.76$ days) and ^{140}La ($T_{1/2} = 40.28$ h) as well as for the fission product mass chain yield. For the latter the data reported in [5] were used. The former problem is solved by starting the counting at least two weeks after the irradiation in order to wait for the decrease of ^{140}La. In this case it can be demonstrated [12] that the correction due to the radioactive equilibrium (see Appendix A) is a constant given by:

$$\phi(\mathrm{t},\tau) = \lambda_{\mathrm{La}}/(\lambda_{\mathrm{Ba}} - \lambda_{\mathrm{La}}) = 1.1516 \tag{4}$$

Since the irradiated Uranium foils were bare a further correction was needed to account for the fission fragment escaping from the foils. The data from [13] were used.

A full description of the fission reaction rates measurements is given in [12]. This last reference reports also the correction for the contribution to ^{235}U(n,f) fission due to the small amount of ^{238}U present in the foil. This contribution is about 1% at the core centre and results negligible in the Radial-1 position.

The results of ^{235}U(n,f) measurements are reported in Table 3. The total error quoted for the fission reaction rates accounts for the errors already discussed for the activation reaction rates plus that one due to the fission chain yield ($\pm$2.6%).

Previous calculations [9] give the average ^{235}U(n,f) cross section, in several positions inside the reactor, including the Radial-1 channel. It is thus possible to get the total flux by the ^{235}U(n,f) reaction rate measurement also in the Radial-1 experimental position, provided that the new reactor configuration does not affect very much the neutron spectrum at the Radial-1 position and hence the ^{235}U(n,f) fission cross section.

To verify this hypothesis the unfolding procedure for Radial-1 channel was applied to the data obtained for the "reference" reactor condition taken from [3]. The used data (reaction rates) are reported in Table 4, while, in Fig. 4, a comparison of the normalised (to 1) neutron spectrum in Radial-1 position before ("reference") and after (present) TAPIRO modification is shown.
This unfolding pointed out that the total flux in the "reference" condition:

$$\Phi_{\mathrm{RC}}^{\mathrm{ref}} = 1.75 \cdot 10^{10} \mathrm{n/cm^2/s} \quad \text{at 100 W} \tag{5}$$

is about a factor 2 lower than the present value (1) and that the two neutron spectra are very close (see Fig. 4).

If the two total neutron flux values are used to calculate the fission cross section in Radial-1 channel we found the two data agree within 10% (Table 3). This demonstrates that the ^{235}U fission rate measurement approach is correct to verify the total flux level in the Radial-1 channel.

5 Preliminary Conclusion on the TAPIRO Reactor Calibration

The results reported in Table 3 for the total flux in the Radial-1 position obtained by the ^{235}U(n,f) reaction rate measurements are directly comparable with the total flux obtained by the unfolding method. The two results agree within 3%. The final result for the total flux, in the Radial-1 channel, is

$$\Phi_{\mathrm{RC}} = 3.8 \cdot 10^{10} \mathrm{n/cm^2/s} \quad \text{at 100 W.} \tag{6}$$

This figure is about *twice* that obtained in the same position in the "reference" condition for the TAPIRO and it is in agreement with the total flux at the TAPIRO core centre which has been measured, in the present work, with the ^{235}U fission rate.

To conclude we can state that the ^{235}U(n,f) fission rate measurement confirmed the neutron flux level found by the unfolding method, demonstrating that the modification of the TAPIRO reactor conditions are not negligible.

Appendix A: Absolute Radiometric Measurement: an overview

Three HPGe detectors (of 50%, 40% and 30% relative efficiency) are available at the Frascati Neutron Generator (FNG) laboratory [14]. The one at 30% of relative efficiency is also provided with a thin beryllium window in order to measure low energy gamma rays (till 3 keV). The detectors are shielded by commercially available lead shields 10 cm thick with cadmium and copper internal layers to reduce the scattering effects. They are absolutely calibrated, (at distance of 10 cm or more) in the energy range from 59 keV up to 1836 keV, by using a selected set of calibration sources. These sources are calibrated at 1.0% $\div$ 2.5% at 1σ level. The calibration curve is obtained by mean of a best fitting procedure using a polynomial approximation. Usually the calibration curve uncertainty is at $\pm$2% $\div$ $\pm$3% at 1σ level. Intercalibration of the three detectors is routinely performed using activated foils in order to check the consistency of the results. Interlaboratory calibrations have been also performed [1)].

Low level activated samples are counted in close geometry. In this case a sample of the same dimension is irradiated with the 14 MeV Frascati Neutron Generator. The sample is thus measured both at the calibrated position and in close geometry. An internal calibration factor (K_{in}) is obtained as ratio of these two measurements. K_{in} includes the geometric corrections as well as the coincidence summing corrections. Using K_{in}, the reaction rate measured in close geometry is referred to the absolutely calibrated distance.

The data acquisition and analysis system is that commercially available from Ortec, as well as the processing electronics. Once a spectrum has been analysed, the peak of interest is used to calculate the absolute reaction rate $\sigma\Phi$, via the following equation :

$$< \sigma\phi >= \frac{C_0 e^{\lambda t_r}}{F(\lambda, T_{irr})\epsilon m w P_\gamma N_0 Y_j \phi(t,\tau)} \cdot \frac{\lambda}{1 - e^{-\lambda t_c}} a_\mu K_G A \tag{7}$$

where: C_0 is the measured peak area; $e^{\lambda t_r}$ is the correction due to the sample cooling time t_r; $1/(1 - e{-}\lambda t_c)$ is the correction due to the counting time t_c; $F(\lambda, T_{irr})$ is the fraction of nuclides activated during the irradiation period T_{irr}; m is the sample mass; w is the isotope fraction (in percent) in the natural composition; P_γ is the the gamma ray emission probability; N_0 is the Avogadro number; A is the atomic mass, a_μ is the self-absorption correction; K_G is the geometric correction factor. As far as the $F(\lambda, T_{irr})$ factor is concerned, it is calculated accounting for the true neutron irradiation profile. Y_j is the mass chain fission yield (only for fission rate measurement) otherwise $Y_j = 1$, and $\phi(t,\tau) \neq 1$ if there is a radioactive equilibrium else $\phi(t,\tau)=1$.

As regards the total error to be quoted for each measure, it is calculated using the quadrature propagation law. The typical total error range from 2.5% up to several percent for low activated sample, in the last case the overall contribution comes from the peak area. Other contributions are due to the detector efficiency ($\pm$2% $\div\pm$3.5%, including the error for K_{in}), nuclear data (P_γ, a_μ usually $<$1%), and geometry ($\pm 1 \div 2$%).

[1)] Courtesy of D. Cockerill, a check with the RAL detector has been possible.

Part II

Neutron irradiation of Avalanche Photodiodes in the Tapiro reactor

6 Radiation Damage Tests on Avalanche Photodiodes

The Avalanche Photodiodes under study are silicon devices, in which the photosensitive face is covered by a thin Si_3N_4 layer. The particular doping profile of the APD creates a thin region (few μm) of intense electric field where an avalanche takes place and thus the signal due to the photo-electrons is increased by some gain, which is tipically of the order of 50-100. The gain 50 is reached for a bias of few hundreds Volts. (A more detailed description of the APD working principle and of radiation damage studies is given in Ref [15]).

The current prototypes have been optimized with respect to radiation hardness. The total neutron fluence for 10 years of data taking at the LHC, corresponding to an integrated luminosity of $5{\cdot}10^5$ pb^{-1} in the APD region has been estimated in [1] to $2{\cdot}10^{13}$ n/cm^2 and the γ dose to 3-5 kGy. This γ dose has been proved to give no significant effect on the APDs.

The neutrons cause displacements of atoms from the silicon lattice, thus creating localized defects. Some of these defects can have associated energy levels for electrons and holes which cause an increase in the dark current. The more defects in the silicon bulk, the higher will be the dark current of the device. And thus the increase in the dark current is expected to be linear with the fluence.
Because this behaviour is typical of many silicon detectors (see [16]), it is used to parametrize the linear dependence of the neutron-induced dark current $\delta \mathrm{I_D}$ from the fluence Φ as:

$$\delta \mathrm{I_D} = \alpha \mathrm{V} \Phi \tag{8}$$

where V is the active volume of the device and the α parameter represents the rate of increase of the current with the fluence.

For the APDs it is reasonable to assume that the volume which is effective in producing the bulk current is given by the area of the device times the effective thickness $\mathrm{d_{eff}}$. The latter is the thickness seen by an ionizing particle crossing the medium and for the Hamamatsu APDs used in this investigation it is of the order of 5 μm (for more details see [1]).

Care must be used when evaluating the α parameter because:

- the dark current strongly depends on the temperature at which the measurements are done;
- the radiation-induced dark current partly recovers with time, and this recovery is particularly evident in the first few days after the irradiation;
- the recovery of the dark current depends on the temperature at which the devices are stored [17]: for example if they are stored at low temperature (below 0^{o}C) almost no recovery occurs;
- the radiation damage depends on the particle type and energy (see Section 7).

Even though the measurement of the dark current is in principle easy to do, the correct calculation of the α parameter should take into account all the various factors which come into the game.

6.1 Irradiation Facilities used by the CMS-ECAL Collaboration

To test the APD radiation resistance it is worth to span the range of fluence from $1{\cdot}10^{11}$ to $2{\cdot}10^{13}$ neutrons/cm^2.

In the CMS-ECAL Collaboration there are several sources available for the irradiations with neutrons and protons.

- Among the neutron sources there are two reactors:
  - TAPIRO reactor at ENEA-Casaccia
  - Ulysses reactor in Saclay,

- a ^{252}Cf source in Oak-Ridge, whose average neutron energy is at about 2 MeV,
- a neutron spallation source (energy around 1-2 MeV) which makes use of the proton beam of ISIS at RAL,
- the proton beam of PSI in Villigen, where protons up to 400 MeV/c are available.

In all these facilities the maximum fluence required, $2{\cdot}10^{13}$ neutrons/cm^2, is cumulated in less than 1 hour, except for the Oak-Ridge neutron irradiation where it takes about 30 days.

This investigation has been done to understand a disagreement of a factor 2 found between the damage occurred to the same device in the RAL and Oak-Ridge irradiations with respect to Rome and PSI, and a factor 4 with respect to Saclay (see Figure 4.11 in [1], page 119).

7 Non-Ionizing-Energy-Loss (NIEL)

The damage induced in the silicon devices by neutrons and protons is of comparable intensity at high energy because the defects in the lattice are mainly created by the recoil products of the collisions initiated by the impinging particles. The main difference between neutron and protons is then the ionizing energy loss, which is not so effective for the damage. At low energy there are larger differences between protons and neutrons damage which are due to resonances in the cross-sections.

To compare the various irradiation results 1 MeV neutrons are taken as a reference and to rescale the damage of all other sources to it with the so-called NIEL factor. The NIEL factor is the Non-Ionizing-Energy-Loss released by the particle in the medium relative to 1 MeV neutrons. This quantity is shown in Figure 5 for silicon (data from [18]). From this figure it is evident the presence of many resonances in the low energy region while at high energy different particles give similar effects. It must be stressed that there are uncertainties in the literature on the NIEL calculations which are of the order of 10-20%.

To compare different irradiation facilities it is of the outmost importance the detailed knowledge of each energy spectrum and the calculation of the NIEL factor.

7.1 Evaluation of the NIEL factor for the Tapiro reactor

From the data in Figure 5 and the energy spectra as evaluated with the unfolding method, it is possible to calculate the NIEL factor for the Tapiro reactor (and the other neutron sources).

Table 5 shows the NIEL factors for the Tapiro where the energy spectrum was measured: in the diametral channel (core), in the radial channel, and in the radial channel for the "*reference*" data of 1985.

As described in Section 4.1, 3 APDs were irradiated together respectively in the radial channel (RC), in the diametral channel (DC) and in the thermal column (TC), each with an uranium foil, that, as discussed in Section 4.2, was used to measure the absolute flux in the corresponding positions. Table 6 shows the dark current measured for these 3 APDs after the irradiation. No direct measurement of the neutron spectrum in the thermal column was done and so no estimate of the NIEL parameter can be given for this region. Nevertheless, it is possible to evaluate the value of the NIEL factor for the neutron spectrum in the thermal column from the ratio of the currents induced in the APDs in the thermal column and in the radial channel, the fluences measured in Table 3 with the Uranium foils for the radial and thermal channels and the NIEL calculated for the radial channel (see Table 5), as:

$$\mathrm{NIEL_{TC}} = \frac{\mathrm{I_{TC}}}{\mathrm{I_{RC}}} \cdot \frac{\Phi_{\mathrm{RC}}}{\Phi_{\mathrm{TC}}} \mathrm{NIEL_{RC}} = 0.23. \tag{9}$$

Table 5 also shows the NIEL factor for the FNG facility, an almost monochromatic neutron source of 14 MeV described in Section 9.2.

8 Irradiation of the APDs at the TAPIRO reactor in Rome

Beginning in september 1996, about 20 APDs have been irradiated in the TAPIRO reactor in Rome. They were irradiated in the radial channel, at 10 cm from the reactor core. The fluence on the APDs depends on the time of exposure and on the power of the reactor. The irradiations are usually chosen to take 20-30 minutes, thus the power of the reactor is chosen to cumulate the requested fluence in the given time. The 20-30 minutes exposure time has been chosen because it is reasonable for the operation of the reactor and it is long enough to neglect the

ramp time of the reactor up to the given power and down (of the order of one minute). Thus the uncertainty of the total administered dose is of the order of 10 %.

The available space in the Radial Channel, see Figure 1 allows the irradiation of at most two APDs at a time. In 1998 a more extensive irradiation campaign was done (of about 100 samples) and then also the thermal channel was used.

The α parameter for the APDs irradiated in the various facilities is summarized in Table 7 together with the fluence and NIEL of each facility.
The α parameter in the Table is calculated as:

$$\alpha = \frac{\mathrm{I_B}}{\mathrm{V}\Phi_{\mathrm{norm}}} = \frac{\mathrm{I_B}}{\mathrm{A}\mathrm{d_{eff}}\Phi\mathrm{NIEL}} \tag{10}$$

where $\mathrm{I_B}$ is the bulk current at 18 $^{\circ}$C and 2 days after the irradiation, the volume V of the device is calculated as the area A times the effective thickness $\mathrm{d_{eff}}$ of the devices and the fluence Φ_{norm} is given by the fluence times the NIEL factor.
The main contributions to the error on α arise from the uncertainties on the fluence (of the order of 10 $\%$) and on the extrapolation of the current $\mathrm{I_B}$ from the day and temperature of the measurements to 18°C and 2 days after the measurement (for which an accuracy of 10 $\%$ can be assumed). Thus the error on α is of the order of 15 $\%$. The uncertainty in the calculation of the NIEL factor has not been included in the error quoted in Table 7.

Three types of APDs have been irradiated: an old type (marked as BC) and two more recent types (serie 400 and 200), both from Hamamatsu. The area of the old type is 0.2 cm^2, while for the new types it is 0.25 cm^2. The performances under irradiation of the old and new APDs are very similar, thus an effective thickness of 5 μm has been assumed for all types.

The fluences in Table 7 in the radial and diametral channel were evaluated from the flux, as calculated from the unfolding in Table 3. The NIEL calculation is described in Section 7.1.

The 3 APDs marked as (U) in the Table have been irradiated together respectively in the radial channel (RC), in the diametral channel (DC) and in the thermal channel (TC), as described in Section 4.1 each with an Uranium foil. The α parameter for the two APDs in the Radial Channel and in the Diametral channel (in the core) are in good agreement. It is important to stress that for these two, the neutron energy spectra, the fluences and the method of calibration are all different. So these two can be regarded as independent measurements, that confirms the consistency of the whole calibration procedure. The irradiations in the thermal column of several other APDs (from Ha.-403 to Ha.-417) consistently confirm the NIEL estimated from the APD Ha-418 in Section 7.1.

9 Other irradiation tests

To check the results on the radiation damage obtained at the Tapiro reactor two other irradiation tests were performed in two different facilities which have different neutron spectra and absolute calibrations: the Frascati Neutron Generator and the Ljubljana reactor. These two irradiation facilities are not part of the standard CMS ones and the irradiation in these has been done only for cross-check.

9.1 Irradiation at the Ljubljana reactor

One APD was irradiated (courtesy of G. Casse) with the TRIGA reactor in Ljubljana [19] with a dose of $2.09 \cdot 10^{13}$n/cm^2, with an accuracy of 10 $\%$. The NIEL for this reactor spectrum is 0.79. This factor has both been calculated and verified with several irradiations on silicon devices by the ROSE Collaboration [20].

The bulk current measured for this APD is 217.8 nA at 18°C and 2 days from the irradiation. From this APD we can estimate $\alpha = (13.1 \pm 2.0) \cdot 10^{-17}$ A/cm/n. This single result is slightly larger, but compatible with the others.

9.2 Irradiation with 14 MeV neutrons in the Frascati Neutron Generator

A cross check of the results obtained at TAPIRO was done irradiating one APD with 14 MeV neutrons. The irradiation was performed at the Frascati Neutron Generator [14] (FNG) of ENEA Frascati (Fig. 6).

FNG is based on the T(d,n)^{4}He fusion reaction to produce 14 MeV neutrons. A beam of deuterons (up to 1 mA, produced by a duoplasmatron type ion source) is accelerated up to 300 keV onto a titanium-tritiated target. The titanium layer (24 mm in diameter) is deposited on the bottom of a copper cup which is housed in a 1 mm thick

support (made of stainless steel) designed to minimise neutron scattering. The beam power is removed by water flow. The D-T reaction is isotropic in the centre of mass frame and the source intensity is up to $1.0{\cdot}10^{11}$n/s. FNG is hosted in a large concrete bunker which allows for the neutron room background to be minimised.

At FNG the neutron yield is monitored by a silicon surface barrier detector which counts the associated alpha-particle emission. The absolute neutron yield is calibrated at $\pm 2\%$ [21]. The main uncertainty in the fluence evaluation comes from the sample-target distance (± 1 mm).
In this case, the APD was located 17 mm far from the target surface (Fig. 6), the irradiation lasted 4500 s and the total fluence was $1.51{\cdot}10^{12}(\pm 6\%)$ n/cm^2.

The irradiation neutron flux spectrum was calculated by Monte Carlo code `MCNP-4A` [22]. From the calculated spectrum it can be concluded that more than 92.5% of the neutrons are in the energy range between 14 MeV and 15.7 MeV (more than 50% of the flux is between 14.4 MeV and 14.9 MeV). Using this spectrum the NIEL was calculated resulting 2.22.

The APD measured in this source gives 32 nA of bulk current at 18^{o}C and 2 days from the irradiation. From this APD we can estimate $\alpha = (9.6 \pm 1.1) \cdot 10^{-17}$ A/cm/n.

The last two lines of Table 7 show a comparison between the APD irradiated in the FNG facility and another one of the same type irradiated in the Radial Channel of the Tapiro reactor. The evaluation of the α parameter is in good agreement between the two.

10 Conclusions on the neutron radiation damage on the APDs

In this investigation four independent irradiations were considered:

- the radial channel of the Tapiro reactor,
- the diametral channel of the Tapiro reactor,
- the Frascati Neutron Generator,
- the Ljubljana reactor.

The energy spectra of the 4 facilities are very different, the doses were estimated with different methods and good agreement is found between the α parameters as evaluated in the first three cases. A value of α which is slightly larger is found for the irradiation in the Ljubljana reactor.

Figure 7 contains the new points which concern the new irradiation facilities (Ljubljana and FNG) and the old data with the newly measured fluence for the Tapiro reactor. This Figure must be compared with the previously published Figure 4.11 in [1].
For what concerns the newly measured fluence of the Tapiro rector, notwithstanding the fact that this calibration gives almost a factor of two higher fluence, the NIEL was evaluated giving a factor of nearly 1/2 in the Radial Channel. Thus the data points remain almost unchanged.

After this investigation, a better agreement with the PSI results is obtained, but the discrepancy with the Oak-Ridge and RAL sources remains. The recent irradiations done in Ljubljana and in particular in FNG tend to confirm the Tapiro and PSI data. For what concerns the data of the Saclay reactor, a new calibration will be done soon by the Saclay group with a method similar to the one performed in this note.

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Reaction	$\sigma\Phi$ (1/atom 1/s)	Error (%)
$^{197}\mathrm{Au(n,\gamma)}^{198}\mathrm{Au}$	2.12E-14	± 3.0
$^{55}\mathrm{Mn(n,\gamma)}^{56}\mathrm{Mn}$	4.17E-15	± 3.0
$^{235}\mathrm{U(n,f)}$	6.57E-14	± 4.0
$^{115}\mathrm{In(n,n')}^{115}\mathrm{In^m}$	9.61E-13	± 3.0
$^{58}\mathrm{Ni(n,p)}^{58}\mathrm{Co}$	2.50E-16	± 3.0
$^{27}\mathrm{Al(n,\alpha)}^{24}\mathrm{Na}$	2.06E-18	± 5.0
$^{59}\mathrm{Co(n,\alpha)}^{56}\mathrm{Mn}$	5.65E-19	± 9.0

Table 1: Nuclear reaction and experimental reaction rates used for the unfolding of the TAPIRO spectrum at the Radial-1 experimental position.

Reaction	$\sigma\Phi$ (1/atom 1/s)	Error (%)
$^{63}\mathrm{Cu(n,\gamma)}^{64}\mathrm{Cu}$	4.46E-14	± 3.0
$^{197}\mathrm{Au(n,\gamma)}^{198}\mathrm{Au}$	3.35E-13	±3.0
$^{235}\mathrm{U(n,f)}$	2.74E-12	±3.0
$^{237}\mathrm{Np(n,f)}$	2.12E-12	±3.0
$^{238}\mathrm{U(n,f)}$	4.05E-13	±3.0
$^{115}\mathrm{In(n,n')}^{115}\mathrm{In^m}$	2.78E-13	±3.0
$^{47}\mathrm{Ti(n,p)}^{47}\mathrm{Sc}$	2.36E-14	±3.0
$^{58}\mathrm{Ni(n,p)}^{58}\mathrm{Co}$	1.39E-13	±3.0
$^{46}\mathrm{Ti(n,p)}^{46}\mathrm{Sc}$	1.44E-14	±4.0
$^{48}\mathrm{Ti(n,p)}^{48}\mathrm{Sc}$	3.69E-16	±4.0
$^{27}\mathrm{Al(n,\alpha)}^{24}\mathrm{Na}$	8.99E-16	±4.0

Table 2: Experimental reaction rates at the core centre of the TAPIRO reactor at the nominal power of 5 kW obtained in the "reference" condition. Data from ref. [3].

Exper. position	Fission rate of ^{235}U(n,f) (1/atom 1/s)	Unfolded Neut. Flux (n/cm^2/s)	^{235}U(n,f) Neut. Flux (n/cm^2/s)	Calculated σ_{fiss} (barn)	(this work) σ_{fiss} (barn)
Core Centre	9.40E-14 ± 5%	4.76E+10 (*)	7.40E+10± 7%	1.27	
Radial-1	6.57E-14 ±5%	3.70E+10 (this work)	3.80E+10 ± 10%	1.58	1.73
Th. Column	1.10E-14±6%	–	9.0E+08 ± 15%	12.2	–

Table 3: Results of the ^{235}U(n,f) fission rate measurements in the various experimental positions. The various columns show:
The experimental position,
Fission rate at the nominal power of 100 W,
Unfolded neutron flux at the nominal power of 100 W,
Neutron flux calculated using the ^{235}U(n,f) reaction rate,
Calculated average fission cross section (from Ref. [9]),
^{235}U fission cross section obtained in the present work.
(*) the unfolding for this value was done using the reference conditions, data from Ref. [3].

Reaction	$\sigma\Phi$ (1/atom 1/s)	Error (%)
$^{50}\mathrm{Co(n,\gamma)}^{60}\mathrm{Cu}$	9.23E-16	±3.0
$^{239}\mathrm{Pu(n,f)}$	2.71E-14	±3.0
$^{235}\mathrm{U(n,f)}$	2.55E-14	±3.0
$^{237}\mathrm{Np(n,f)}$	7.05E-15	±3.0
$^{238}\mathrm{U(n,f)}$	7.31E-16	±3.0
$^{115}\mathrm{In(n,n')}^{115}\mathrm{In^m}$	5.36E-16	±4.0
$^{47}\mathrm{Ti(n,p)}^{47}\mathrm{Sc}$	3.27E-17	±4.0
$^{58}\mathrm{Ni(n,p)}^{58}\mathrm{Co}$	1.99E-16	±4.0
$^{48}\mathrm{Ti(n,p)}^{48}\mathrm{Sc}$	4.07E-19	±4.0
$^{27}\mathrm{Al(n,\alpha)}^{24}\mathrm{Na}$	3.69E-16	±4.0

Table 4: Experimental reaction rates at the Radial-1 experimental position of the TAPIRO reactor, at the nominal power of 100 W obtained in the "reference" condition. Data from ref. [3].

Neutron source	NIEL rel. to 1 MeV neutrons
Tapiro (DC)	0.883
Tapiro (RC)	0.463
Tapiro (RC) 1985	0.487
Tapiro (TC)	*0.23*
FNG	2.221

Table 5: Non-Ionizing-Energy-Loss relative to 1 MeV neutrons on silicon, for the various neutron sources. For the Tapiro reactor, the NIEL in the radial channel (RC) and the diametral channel (DC) are estimated from the measured neutron spectrum. For the radial channel, also the "*reference*" data of 1985 are considered [3].
The NIEL in the Thermal Column (TC) is calculated through the damage on the APDs as in (9). The last line shows the NIEL for the FNG facility (described in Section 9.2).

APD type and number	Irrad. Fac.	$\Phi(10^{12}\mathrm{n/cm^2})$	NIEL	$\mathrm{I_B\,(2d,18^oC)(nA)}$
Ha-406	Tapiro-RC	48.6	0.46	225
Ha-242	Tapiro-DC	62.8	0.88	702
Ha-418	Tapiro-TC	0.115	*0.23*	2.679

Table 6: Data concerning the 3 APDs which were irradiated each with the Uranium foils: fluence, NIEL and bulk current at 18°C and 2 days after the irradiation. The APDs were irradiated in the Tapiro reactor in the Radial Channel (RC), in the Diametral Channel (DC) and in the Thermal Channel (TC).

APD type and number	Irrad. Fac.	$\Phi(10^{12}\mathrm{n/cm^2})$	NIEL	$\mathrm{I_B\,(2d,18^oC)(nA)}$	$\alpha(10^{-17}$ A/cm/n)
Ha-423	Tapiro-RC	48.6	0.46	296	(10.4± 1.5)
Ha-406 (U)	Tapiro-RC	48.6	0.46	225	(10.0± 1.5)
Ha-242 (U)	Tapiro-DC	62.8	0.88	702	(10.2± 1.5)
Ha-418 (U)	Tapiro-TC	0.115	0.23	2.679	–
Ha-403	Tapiro-TC	11.5	0.23	245	(10.3± 1.5)
Ha-404	Tapiro-TC	11.5	0.23	261	(11.0± 1.6)
Ha-405	Tapiro-TC	11.5	0.23	247	(10.4± 1.5)
Ha-413	Tapiro-TC	11.5	0.23	249	(10.5± 1.5)
Ha-414	Tapiro-TC	11.5	0.23	236	(10.0± 1.5)
Ha-415	Tapiro-TC	11.5	0.23	255	(10.8± 1.6)
Ha-416	Tapiro-TC	11.5	0.23	248	(10.5± 1.5)
Ha-417	Tapiro-TC	11.5	0.23	244	(10.3± 1.5)
Ha-402	Ljubljana	20.9	0.79	271	(13.1± 2.0)
BC-17	FNG	1.51	2.2	32	(9.6± 1.1)
BC-5	Tapiro-RC	0.2 - 43	0.46	2 - 365	(10.0± 2.0)

Table 7: Summary of the irradiation data from the various APDs in the various irradiation facilities: fluence, NIEL, bulk current at 18°C and 2 days after the irradiation, α parameter measured for each APD. The three APDs marked with (U) have been irradiated at the same time. In the Tapiro reactor the APDs were irradiated in the Radial Channel (RC), in the Diametral Channel (DC) and in the Thermal Channel (TC). The results concerning the APD Ha-402, irradiated in the Ljubljana reactor, are discussed in Section 9.1, while the results concerning the APD BC-17, irradiated in the FNG facility, are discussed in Section 9.2.

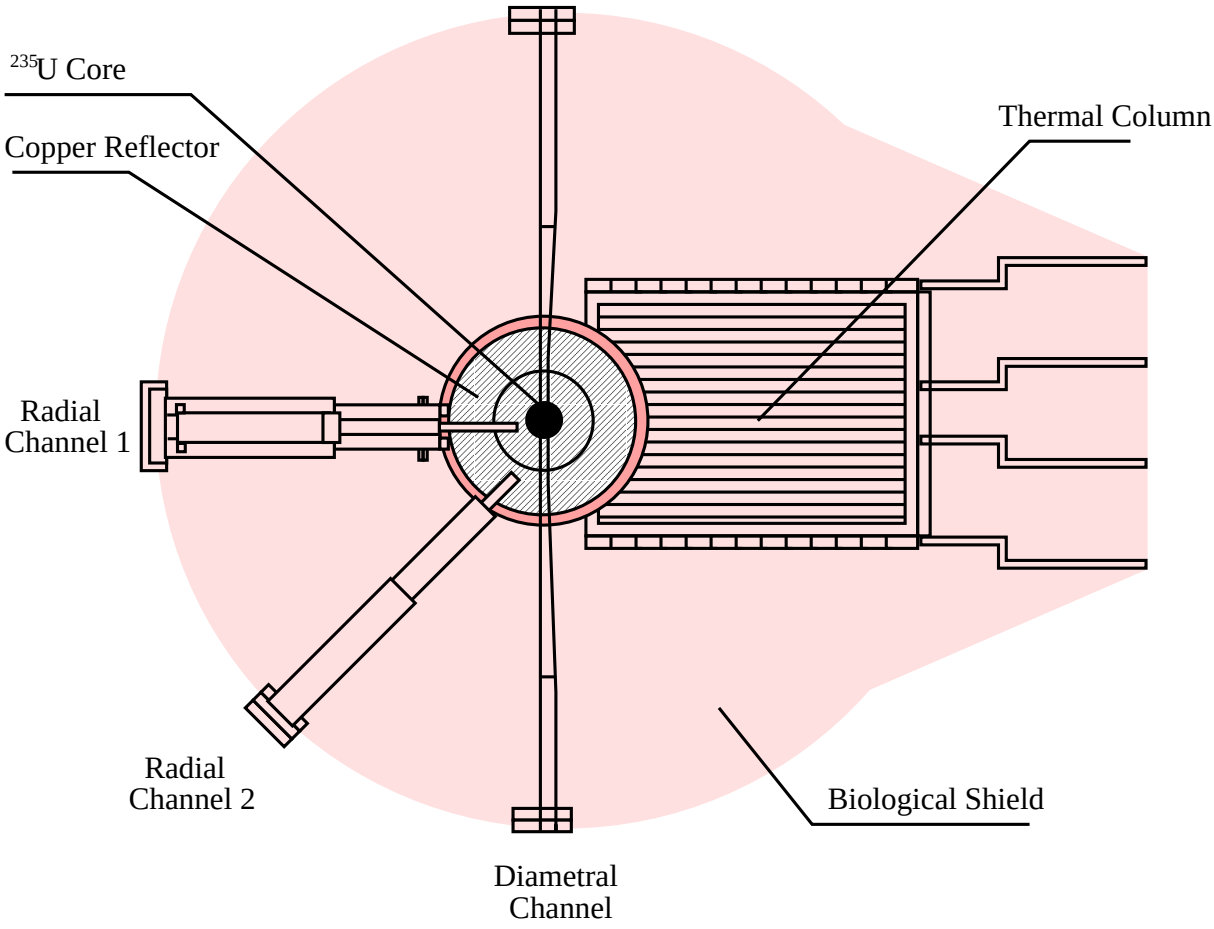


Figure 1: Horizontal cut of the TAPIRO fast source reactor with a general view of the experimental channels and of the Thermal column cave.

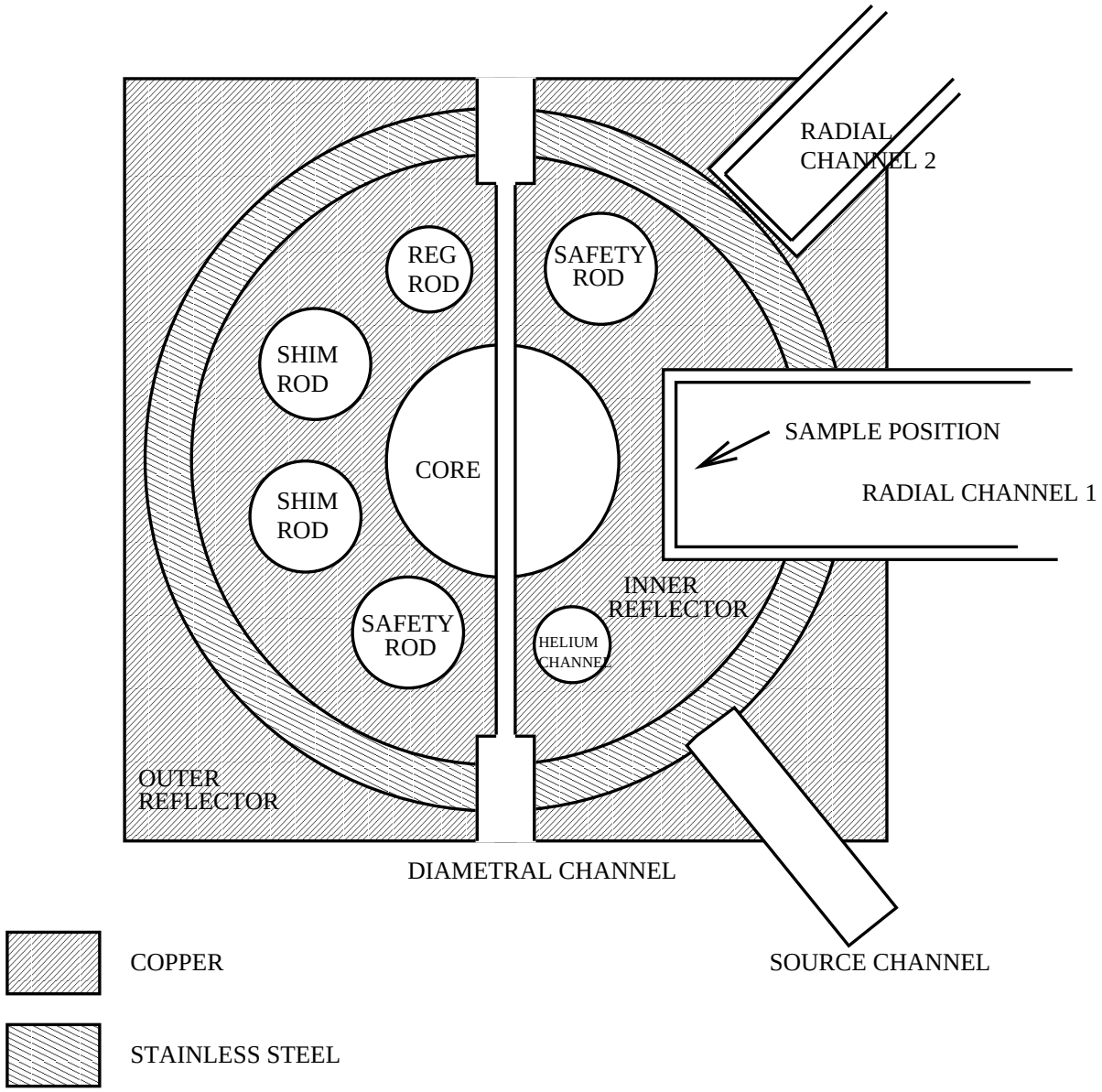


Figure 2: Detail of the TAPIRO core surrounded by the copper reflector. The Radial-1 channel and the diametral channel are evidenced.

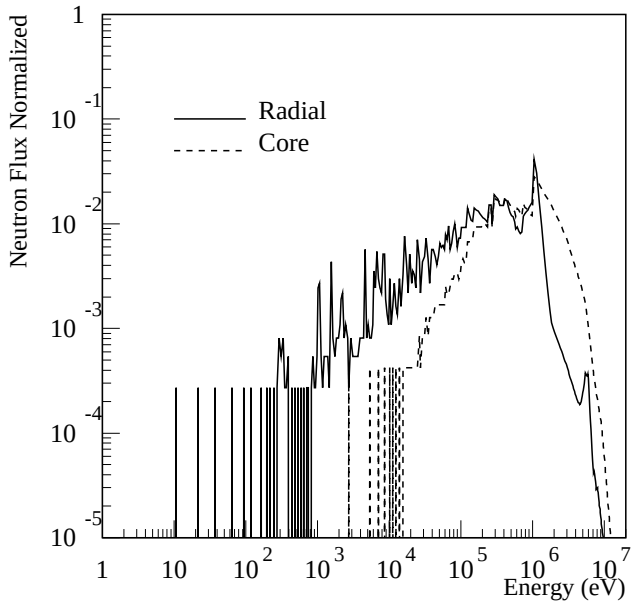


Figure 3: Comparison between the normalised neutron flux spectrum at the core centre and at the Radial-1 channel obtained by the SAND-2 unfolding code.

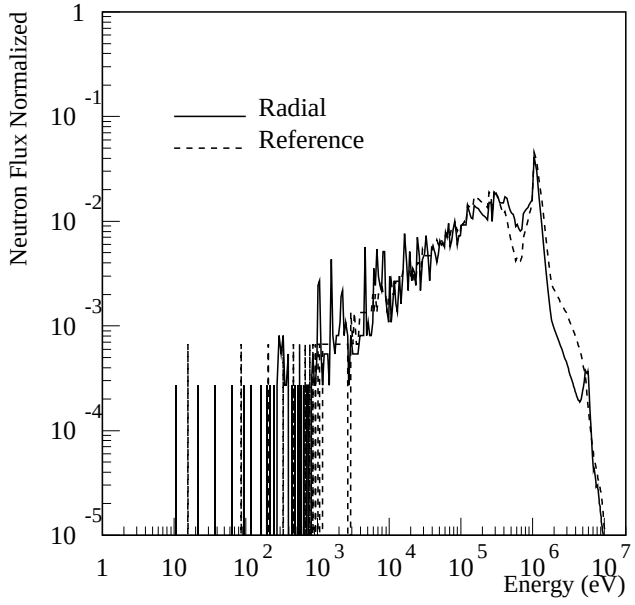


Figure 4: Comparison between the neutron spectra unfolded in the Radial-1 position using the data from the "reference" configuration and the one measured in the present work.

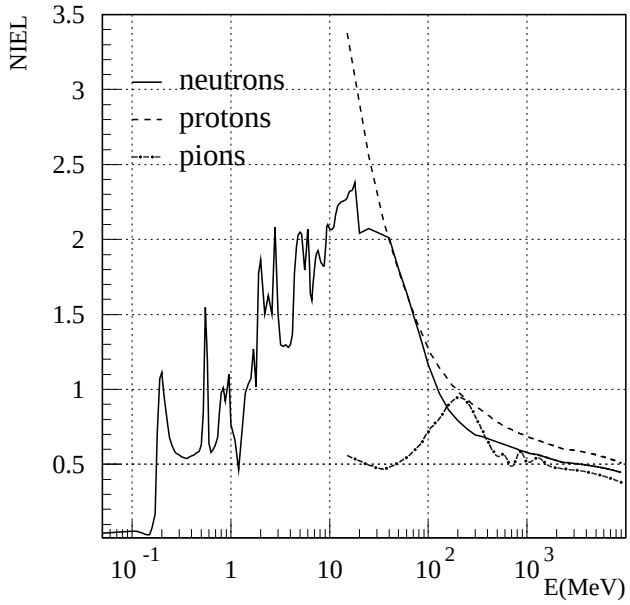
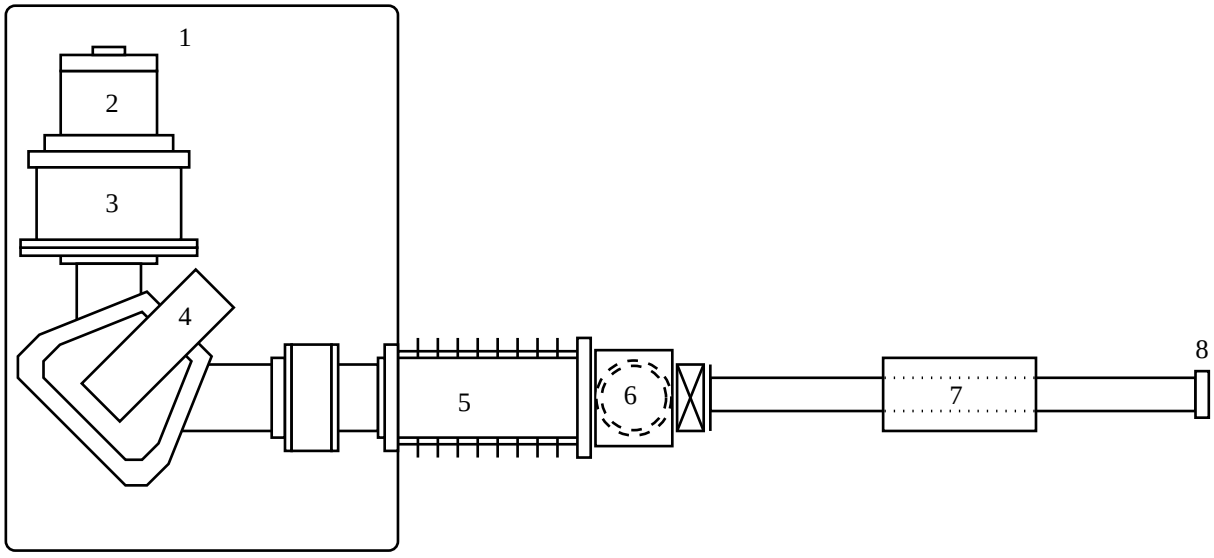


Figure 5: Non Ionizing Energy Loss for neutrons, protons and pions in Silicon, relative to 1 MeV neutrons (data from ASTM supplied by M. Huhtinen, as in [18]).



1 HV Terminal
2 Ion Source
3 Extraction Optics
4 Bending Magnet
5 Accelerating Tube
6 Vacuum System
7 Q-Lens
8 Target

Figure 6: The Frascati Neutron Generator.

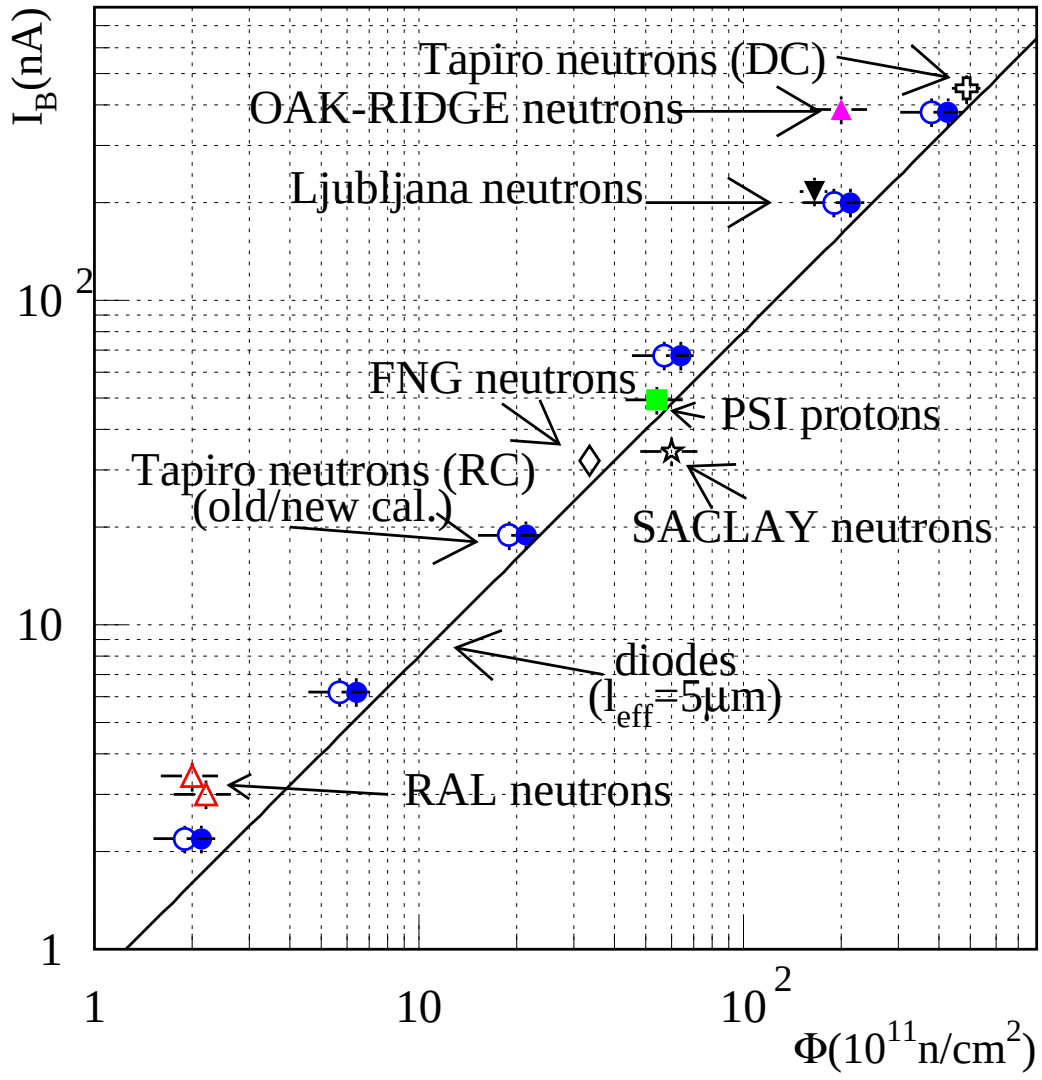


Figure 7: Radiation induced bulk current for the APDs irradiated in several facilities. All the data are measured at 18^{o}C and about 2 days after the irradiation. For the Rome data, the open circles indicate the old calibration of the Tapiro while for the dark dots the flux of this investigation is used. With respect to the Figure published in the TDR, the errors on the fluences regarding the Tapiro neutrons have been reduced, thanks to the new calibration and to the measurement of the NIEL factor. The new measurements done at the FNG and at the Ljubljana reactor have been included.