PAST, PRESENT AND FUTURE ACTIVITIES FOR RADIATION EFFECTS TESTING AT JULIC/COSY

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Abstract

The testing of radiation effects (displacement damage, single event effects) with energetic protons for electronics used in space and accelerators is of growing importance. Setup and past experience of a dedicated test stand used by Fraunhofer INT at the JULIC cyclotron will be presented. During solar proton events, as well as at high energy accelerators (CERN, FAIR), electronics are confronted with protons of much higher energy. Recent scientific studies have shown that for single event upsets as well as destructive failures (e.g, single event latch-ups) a cross section measured at energies in the tens or one/two-hundred MeV range (e.g. PIF@PSI) can significantly underestimate the failure rate. To avoid unnecessary high safety margins there is a growing need for the opportunity to test electronics at several GeV, like the beam provided by the Cooler-Synchrotron COSY in Jülich.

INTRODUCTION

Proton accelerators are a necessary tool for the study of radiation effects in electronics. Protons can produce all kinds of radiation effects, which are generally classified into three categories: effects due to the slow accumulation of ionization (total ionization dose (TID) effects), effects due to transient ionization (single event effects (SEE)), and effects due to the displacement of atoms from their sites in the crystal lattice structure (displacement damage (DD) effects).

While TID effects are usually studied and tested separately with Co-60 gamma sources, proton accelerators are the main tool to study DD effects. The displacement of atoms from their lattice introduces new energy levels in the bandgap of the semiconductor thus affecting its electrical and optical properties [1]. An important quantity for DD effects is the non-ionizing energy loss (NIEL), which for protons increases towards lower energies. For this reason low energy accelerators are very suitable for studying DD effects, provided the beam has enough energy to penetrate the sensitive volume.

Single event effects are noticeable ionization effects produced by a single particle [2]. Protons can produce SEE by two ways. The proton can produce enough charge by direct ionization to trigger an effect e.g. a bitflip (single event upset, SEU) in a memory chip. The equivalent to the NIEL describing ionization effects is the linear energy transfer (LET, in principle the same as the stopping power), which also increases towards lower proton energies. Because protons have much lower LETs as heavier ions, they were until recently not able to produce SEUs by direct ionization. Due to the increasing integration the newest memory technologies have become sensitive to direct ionization by protons [3]. The other way is for the proton to produce recoil atoms or charged fragments by nuclear reactions with the materials in the device. These secondary particles, being heavier ions, have a high enough LET to produce SEE in even quite insensitive devices. While the study of direct ionizing proton SEE calls for a low energy proton accelerator, the study of SEE caused by nuclear reactions needs higher energies.

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This paper will look at the experiences and possibilities to study radiation effects at the JULIC/COSY accelerator facility [4] run by the Institute for Nuclear Physics (IKP) at the Jülich Research Centre (FZJ).

TESTING AT JULIC

For the last 15 years Fraunhofer INT has been operating a dedicated radiation effects test facility at an external beam line of the JULIC cyclotron [5], which can be seen in Fig. 1.

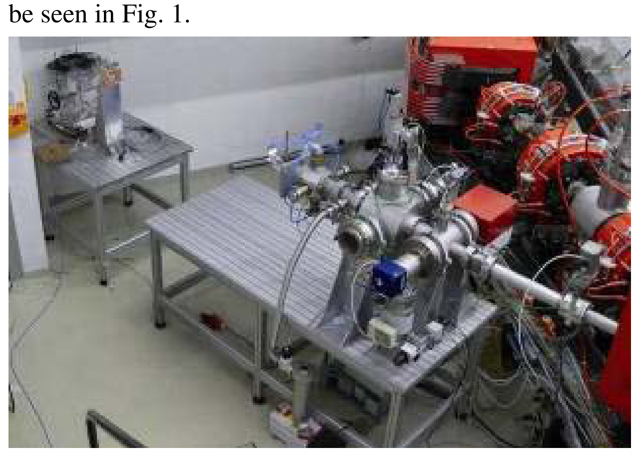

Figure 1: Beam line for radiation tests at JULIC.

The energy of the proton beam is fixed to 45 MeV in vacuum. Since the tests are performed in air, the beam has to pass a 2 mm Al foil and about 1.8 m of air, which reduces the energy of the protons to 35 MeV at the surface of the target. The maximum current is 10 µA, but for the typical fluxes needed for testing, the current is about 5 nA to 10 nA. The usable beam diameter at the target is about 20 cm. The fluence/homogeneity is measured on line with four Farmer 30010 ionization chambers installed and operated by Fraunhofer INT.

As mentioned in the introduction this beamline is mainly used for studying DD effects for space electronics. Especially optoelectronics are sensitive to DD and the investigated parts include photodiodes, LEDs, optocouplers etc. Also tested were electronics from standard parts such as voltage regulators to more exotic devices like GaN HEMTs. Since these tests were confidential work for the space industry, the results were not published.

The investigation of ultraviolet sensitive SiC photodiodes showed high radiation hardness [6]. Fraunhofer INT therefore proposed to use them not only as UV detectors, but also as radiation detectors in harsh environments. This was demonstrated using Co-60 gammas, 14-MeV neutrons at Fraunhofer INT and 35 MeV protons at JULIC [7]

To completely characterize a device for SEEs a proton beam with higher energy is needed (see next chapter). The JULIC beam is, however, useful to investigate the threshold energy for the onset of indirectly produced SEUs. Such tests were for example done on GPS receivers intended for the use on LEO satellites [8].

For the characterization of direct ionization effects a proton beam with a primary energy of 1 MeV to 5 MeV is needed. A recent paper suggests however that for general hardness assurance purposes a degraded 30 MeV proton beam might be feasible [9]. This option will be investigated by Fraunhofer INT further in the future.

(FUTURE) TESTING AT COSY

The majority of the SEE in electronics caused by protons will be caused by secondary particles produced by nuclear reactions. Unlike SEUs caused by direct ionization and DD effects, whose cross sections decrease with higher proton energies, the cross section of these SEEs will increase with higher proton energies. When it will reach saturation strongly depends on the target material.

In [10] the influence of proton energy on single event latchups (SEL) is explored. SEL are destructive SEE that occur specifically in CMOS technology. In a CMOS device there exists an intrinsic n-p-n-p structure, which acts as a parasitic thyristor. The charge produced by an ionizing particle may trigger this thyristor, which results in a high current eventually destroying the device.

Calculations of proton-silicon nuclear reactions show that the recoils have LETs of less than 13 MeV-cm²/mg for proton energies up to 500 MeV [11]. If a device has a threshold for SEL higher than 13 MeV-cm²/mg, established with a heavy ion test, then it should be immune against SEL caused by protons. The tests of several SRAMs in [10] showed however proton induced SEL in devices with a heavy ion threshold of as high as 25 MeV-cm²/mg. The authors claim the SEL on fragments produced by proton-tungsten reactions. Indeed are tungsten plugs commonly used in modern ICs including SRAMs. Calculations in [10] show that the fragments produced by the fragments of proton-tungsten reactions can have LETs of up to 34 MeV-cm²/mg.

In a later proposed test procedure [12] for Proton induced SEL testing for space electronics, it is suggested to test, if possible, at proton energies of 400 MeV or above. The authors justify this with the observation, that this is the highest energy of trapped protons. Although they admit that galactic protons can have higher energies, but their flux is very low. They do not mention, however, the protons of solar events, which can produce on a short time scale of several days significant fluxes of high energy protons [13].

An environment where protons of energies much higher than 400 MeV definitely play a role is the environment of high energy accelerators such as the facility for antiproton and ion research (FAIR) at GSI or the Large Hadron Collider (LHC) at CERN. Figure 2 shows the SEU cross section vs the Proton energy of the ESA SEU Monitor [14]. The SEU monitor is based on 4 Mbit Atmel AT60142F SRAMs using a 0.25 µm CMOS process and is used to compare the dosimetry of different SEE testing facilities [15]. The figure shows experimental data taken at PSI up to 230 MeV as well as two mixed beam points at 120 GeV and 400 GeV at CERN. It shows also simulations done with the FLUKA code [16] for protons up to 100 MeV and neutrons up to 400 GeV. Since the nucleon-nucleus cross sections are the same for protons and neutrons for energies higher than 100 MeV [17] neutrons were used for the simulation due to their lower CPU cost.

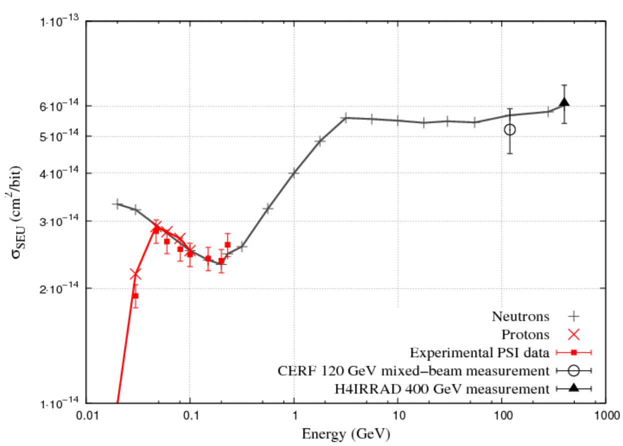

Figure 2: SEU cross section of the ESA SEU monitor.

The simulated SEU cross section curve in Fig. 2 shows a significant rise of about a factor of two at the end of the PSI data of about 200 MeV up to 3 GeV, where it saturates without further change up to 400 GeV. The tests and the simulation were done without removing the lid of the package. This lid has a thickness of 420 µm and consists of Kovar and a gold and nickel plating of 25 µm of each material on each side [14]. The interaction of the proton beam with the materials of the lid produces light fragments, which increase in number and energy as the

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proton energy increases. The higher energy results in a higher range of the fragments, which increases the probability of hitting the sensitive volume.

The results of Fig. 2 show, that if the simulations are correct, the tests with energies up to 200 MeV will seriously underestimate the SEU cross section of the device in a high energy environment. To fully characterize the device a facility would be needed that covers energies up to several GeV. Since, as previously mentioned, the nucleon-nucleus cross section for protons and neutrons is the same above 100 MeV, the discussion about proton environments also extends to neutron environments, not only at accelerators, but also in the terrestrial atmosphere.

The cooler synchrotron COSY at the FZJ is a facility that could fill the need to test at higher energies [4]. The energy range of COSY is from 20 MeV to 2.5 GeV covering the interesting region of Fig. 2. Another advantage is the possibility to change the energy of the beam in relatively short notice. That way there is no need for excessive use of degraders with their inherent drawbacks.

In 2014 the program funding for nuclear physics will end and COSY will be used mainly to investigate new concepts for the HESR accelerator of the GSI FAIR project. This will free some beam time for new uses of the external beam lines. Figure 3 shows a schematic of the layout of the COSY facility. All three external beam lines will be available for new uses.

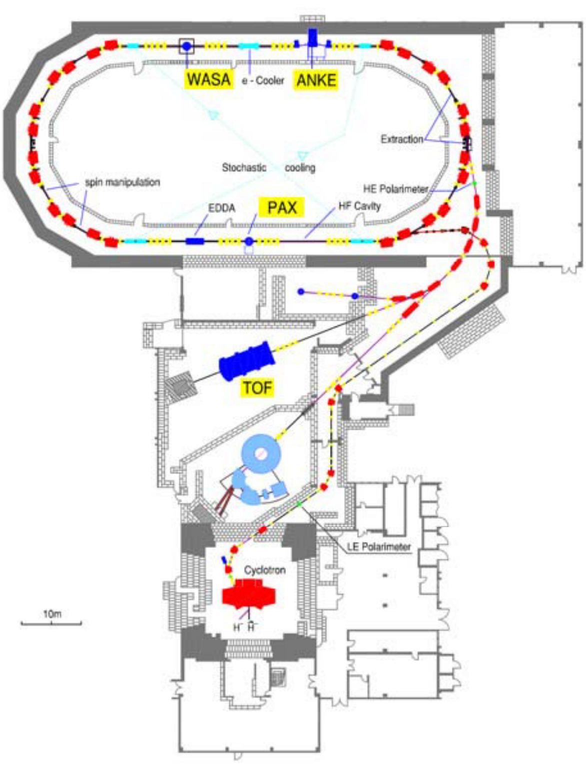

Figure 3: Layout of the COSY facility.

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