Progress of the Scientific Commissioning of a fast neutron beamline for Chip Irradiation

Carlo Cazzaniga and Christopher D. Frost
ISIS Facility, STFC, Rutherford Appleton Laboratory, Didcot OX11 0QX, UK
carlo.cazzaniga@stfc.ac.uk

Abstract. ChipIr is a new beamline at the ISIS spallation source dedicated to accelerated testing of microelectronics. ChipIr features an atmospheric-like neutron spectrum to study the so-called Single Event Effects, a major concern for the reliability of modern electronics at ground level and flight altitudes. A bespoke design was needed to extract a fast neutron beam from a neutron source designed for thermal neutron applications.

The main objective of the Scientific Commissioning is to measure the flux, spectrum and profiles of the fast neutron beam in the different configurations of the beamline. In this work we present preliminary results of fast neutron measurements performed with a 70×70 mm² neutron beam and the accelerator at 700 MeV. The neutron flux above 10 MeV was found to be $4.9 \times 10^6$ cm$^{-2}$s$^{-1}$. The beam profile was found to be uniform within the 70×70 mm² area.

ChipIr is now in an advanced stage of scientific commissioning and beta-users have started the first tests in late 2016. The first ‘official’ deliberate error was measured in a SRAM chip on the 29 June 2016; an 8 bit memory containing 1’s had the 7th bit inverted to a 0 – just the kind of error that can occur in the atmosphere due to neutron interaction.

These results are promising for an imminent start of the ChipIr user programme.

1. Introduction

Atmospheric neutrons are a major cause of Single Event Effects (SEE), which disrupt the correct operation of microelectronics devices and systems. These neutrons are produced by high energy cosmic rays, mainly protons, interacting with the earth’s atmosphere and generating cascading showers of secondary particles [1].

In recent years technology has seen a continuous drive towards miniaturization, low power, faster and ever more complex functionality. Greater vulnerability, combined with an ever greater prevalence of embedded micro-electronic devices, has meant that SEE problems have started to inevitably emerge as a serious issue for terrestrial ground based electronics [2]. The issue is even more important for avionics, because the atmospheric neutron flux is 300 times greater at typical aircraft altitudes with respect to the ground level.

The increasing need for accelerator based facilities to test SEE, particularly in Europe, has motivated a project to design and build a new fast-neutron test facility on the ISIS neutron source at the Rutherford Appleton Laboratory in the UK [3]. ChipIr, for Chip Irradiation, is an instrument designed to mimic the atmospheric neutron spectrum with a flux many orders of magnitude greater than the natural one to enable accelerated testing of electronic devices.
2. The beamline in a nutshell

The ISIS second target station is primarily used to simultaneously deliver thermal and cold neutrons (in the meV energy range) by means of hydrogenous moderators to a variety of instruments for the purpose of condensed matter science. ChipIr is the first instrument on this, or any other similar target station, to deliberately extract an atmospheric-like fast neutron spectrum ($E_n$ up to hundreds of MeV) from such a source.

For this reason, a new section with a channel had to be inserted in the beryllium moderator for the line of view of ChipIr. In fact, the beryllium reflector is a key component of a low-energy neutron target station, being used by all the other beamlines to maximize neutron flux in the moderators.

Neutrons from this channel illuminate a secondary scatterer made with layers of different materials (the details of the scatterer design are confidential at the time of writing). The secondary scatterer is used for two reasons: 1) to optimize the hard atmospheric-like neutron spectrum and 2) to minimize the $\gamma$-ray flux by closing the line of view to the primary target.

ChipIr incorporates a collimator and jaw set to enable the beamline to operate in both ‘flood’ and ‘pencil’ beam configurations. A circular drum and a set of jaws, that can move independently, can define a beam from cm dimension (pencil) up to 0.4 m aperture (flood).

3. Neutron Measurements

The measurements of the beam profile and spectrum within the blockhouse are key for the commissioning of ChipIr. The following neutron measurements have been performed with the current configuration of the beamline, which will be probably changed in some minor details, and the accelerator running at 700 MeV. Therefore, the results have a preliminary connotation; more results will be presented in the coming year. The measurements were made at the forward position, which represent the maximum fluence rate available under the operating conditions, that is, with minimum beam attenuation due to divergence.

Fast neutron detectors included a Single Crystal Diamond Detector $2.0 \times 2.0 \times 0.3$ mm$^3$, with a contact area of $1.5 \times 1.5$ mm$^2$ operated in pulse mode [4, 5], a fission chamber operated in current mode [6], and the Imaging Single-Effect Monitor (ISEEM), a neutron detector based on a CCD sensor [7]. ISEEM is used to benchmark neutron beams used for SEE testing [8].

ChipIr, as with every beamline at the ISIS source, has an independent shutter, so that its neutron beam can be closed and opened while the accelerator is running. The ChipIr shutter is also an active neutronics component, since it hosts the secondary scatterer. The shutter position therefore needs to be optimized. In Figure 1 we show the counting rate on the diamond detector, used at the centre of the beam, as a function of the shutter position. A maximum flux was found at the open position 650 mm. This result is compared in the figure to a measurement performed with the fission chamber and a good agreement is found.

![Figure 1. Neutron flux measurement during a shutter scan using a diamond detector and a fission chamber (Left). A map of the neutron beam measured with a diamond detector (Right).](image-url)
One can notice a sharp increase of the neutron flux from 500 mm to 600 mm opening and a plateau from 600 to 700 mm. Differences can be due to the different size of the detectors and to different energy sensitivity as a function of neutron energy.

During this phase of the commissioning, we tested a collimator configuration that defines a beam of $70 \times 70$ mm$^2$. This dimension was chosen because it provides a typical configuration for electronic device irradiation. A map of the beam was measured using the diamond detector mounted on the XY stage. We demonstrate that this $70 \times 70$ mm$^2$ is uniform and the footprint of the beam is square. This is shown by the map in Figure 1 on the right. There is a good ratio, almost three orders of magnitude, between the centre of the beam and the penumbra.

The Imaging Single-Event effect monitor (ISEEM) was exposed to the ChipIr neutron beam at the centre of the $70 \times 70$ mm$^2$ collimated beam, and used to benchmark the beam against previous exposure at the LANSCE ICE House. This is a relative measurement with respect to LANSCE, which is a reference irradiation facility for electronics cited in JEDEC [9] and IEC [10, 11] standards. Independent measurements of the ChipIr neutron spectrum are being performed using a combination of activation foils technique and proton recoil telescope and results will be presented later in 2017.

The LANSCE-equivalent fluence rate at ChipIr was measured to be $4.9 \cdot 10^6$ cm$^{-2}$ s$^{-1}$ at 40 µA proton current to Target 2, reproducible to within 3%. This flux of ChipIr is about 10 times that at LANSCE operating at 1.8 µA (as in 2005). Figure 2 shows the spectrum of ChipIr compared to LANSCE and the atmospheric one increased by a factor of $10^9$. Here the spectral shape comes from Monte Carlo simulations, but the intensity comes from the value measured with the ISEEM and activation foils.

![Figure 2. Neutron spectrum of ChipIr compared with the atmospheric [9] and LANSCE [12] spectra.](image)

4. Conclusions and Outlook
In this paper we have presented first neutron measurements for the characterization of the ChipIr beamline, which is in an advanced stage of scientific commissioning. ChipIr is an instrument of the second target station of the ISIS spallation source and its neutronics has been designed to extract an atmospheric-like fast neutron beam.
A selected configuration was used for a preliminary characterization with the ISIS accelerator running at 700 MeV. Neutron measurements show a uniform 70 × 70 mm² neutron beam that can be used to irradiate microelectronics devices. An experiment was performed to compare the flux of this beam to LANSCE. The LANSCE-equivalent fluence rate was measured to be 4.9 · 10⁶ cm⁻² s⁻¹ at 40 μA proton current to target 2.

This result is relevant for the forward position, which represent the maximum fluence rate available under the current operating conditions, that is, with minimum beam attenuation due to divergence. The characterization of a rearward position, designed for the flood beam, is in progress.

Moreover, other neutron measurements are needed to understand how the beamline operates in different configurations and how the neutron flux is affected. Spectroscopic measurements are being performed with the accelerator running at both 700 and 800 MeV and the results will be presented later in 2017.

References
[1] M. S. Gordon et al. “Measurement of the Flux and Energy Spectrum of Cosmic-Ray Induced Neutrons on the Ground”, IEEE Trans Nucl Sci 51 (6) 3427 (2004).
[2] R. C. Baumann, “Radiation-induced soft errors in advanced semiconductor technologies” IEEE Trans. Dev. Mat. Rel 5(3) p.305 Sep. 2005
[3] C. Frost, et al. “A new dedicated neutron facility for accelerated SEE testing at the ISIS facility.” Reliability Physics Symposium, 2009 IEEE International. IEEE, 2009.
[4] C. Cazzaniga, et al. “Characterization of the high-energy neutron beam of the PRISMA beamline using a diamond detector”. Journal of Instrumentation, 11(07), P07012 (2016).
[5] M. Rebai, et al. “Response of a single-crystal diamond detector to fast neutrons”, Journ. of Instrum. 8 P10007 (2013)
[6] http://www.lndinc.com/products/category/33/
[7] X. X. Cai and S. P. Platt, "Modeling Neutron Interactions and Charge Collection in the Imaging Single-Event Effects Monitor," in IEEE Transactions on Nuclear Science, vol. 58, no. 3, pp. 910-915, June 2011.
[8] S. Platt et al. "Charge-Collection and Single-Event Upset Measurements at the ISIS Neutron Source," in IEEE Transactions on Nuclear Science, vol. 55, no. 4, pp. 2126-2132, Aug. 2008.
[9] Measurement and Reporting of Alpha Particle and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices, Std. JESD89A, Oct. 2006.
[10] Process management for avionics - Atmospheric radiation effects - Part 2: Guidelines for single event effects testing for avionics systems, IEC 62396-2:2012, 2012.
[11] Semiconductor devices - Mechanical and climatic test methods - Part 44: Neutron beam irradiated single event effect (SEE) test method for semiconductor devices, IEC 60749-44:2016, 2016.
[12] B. Takala, Personal communication, 2005.