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Irradiation setup at the U-120M cyclotron facility

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ABSTRACT

This paper describes parameters of the proton beams provided by the U-120M cyclotron and the related irradiation setup at the open access irradiation facility at the Nuclear Physics Institute of the Czech Academy of Sciences. The facility is suitable for testing radiation hardness of various electronic components. The use of the setup is illustrated by a measurement of an error rate for errors caused by Single Event Transients in an SRAM-based Xilinx XC3S200 FPGA. This measurement provides an estimate of a possible occurrence of Single Event Transients. Data suggest that the variation of error rate of the Single Event Effects for different clock phase shifts is not significant enough to use clock phase alignment with the beam as a fault mitigation technique.

1. Introduction

Tests of radiation hardness are a necessary part of each high-energy physics detector development project and they are needed also in applications where sensitive technologies are exposed to increased radiation levels as it is the case in the space program or aviation. These tests probe resistance and reliability of various materials and electronic components to the expected radiation loads. At present there are many facilities [1–10] which allow to perform such tests using different particle beams and energies.

The radiation facility at the Nuclear Physics Institute (NPI) of the Czech Academy of Sciences, described in this paper, uses proton beams provided by the isochronous cyclotron U-120M in Řež, Czech Republic. It has been widely used to perform radiation hardness tests for the Inner Tracking System (ITS) upgrade project [11] of the ALICE detector [12] at the Large Hadron Collider (LHC) at CERN. Work on this project triggered a development of an on-line monitoring system for low proton fluxes which can be now measured in the range 10^3–10^9 proton cm^{-2} s^{-1}. This paper describes the irradiation setup and gives details about the beam parameters and the associated on-line dosimetry.

Since the ALICE ITS upgrade project played an important role for the extension of the NPI irradiation facility infrastructure for low proton flux measurements, the new ITS detector is briefly introduced in Section 2. Section 3 describes the cyclotron U-120M and gives details about the parameters of the delivered proton beams. The procedure used to measure the proton flux and the corresponding absorbed dose in irradiated samples is discussed in Section 4. Details of the used experimental setup are explained in Section 5. The last section illustrates the use of the described experimental setup for the measurements of possible transient effects in an SRAM-based Xilinx XC3S200 FPGA.

2. ALICE ITS upgrade

The new ALICE ITS [11] will be a silicon tracker with greatly improved performance in terms of impact parameter resolution, tracking efficiency at low transverse momenta, and readout rate capabilities. It will be completely made of specifically designed Monolithic Active Pixel Sensors (MAPS), called ALPIDE chips [13,14]. The upgraded ITS will comprise more than twenty-four thousand ALPIDE chips organized in seven concentric cylindrical layers with a total surface of more than 10 m^2. The system is designed to have a very low material budget (less than 3 per mill of radiation length per layer), high granularity (29 μm × 27 μm pixel size), and low power consumption (<40 mW/cm^2). It will be installed in 2019–2020 [15].

All electronic components which are going to be used in the new ITS detector need to be tested whether they sustain the expected radiation levels. It is anticipated that the innermost layer of silicon sensors will accumulate 270 krad of Total Ionizing Dose (TID) and 1.7×10^{12} 1 MeV n_{eq} cm^{-2} of Non-Ionizing Energy-Loss (NIEL) for the full integrated luminosity [13]. Similarly, the expected radiation levels at the position where the ITS Readout System [16] will be installed are expected to be 1 krad (TID) and 1.6×10^{11} 1 MeV n_{eq} cm^{-2} (NIEL). The flux of hadrons

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with energy higher than 20 MeV which are able to induce a Single Event Upset in the readout electronics is expected to be about 10^3 cm^{-2} s^{-1}. In the project proposal, these levels are further increased by a safety factor of 10 [13].

3. Cyclotron U-120M and proton beam parameters

The cyclotron[1] U-120M was commissioned in 1977, and since then, it has been continuously upgraded [18,19]. Currently, it can be operated in both negative and positive modes.

In the negative mode, the cyclotron can accelerate H^- or D^- ions. The beam extraction is done by means of an about 1 μm thick carbon stripping foil placed at the required final beam orbit. When going through the foil, negative ions lose with a high probability both valence electrons. The resulting protons or deuterons are directed in the cyclotron magnetic field to a short, 3 m long beamline located in the cyclotron hall. At the end of the beamline, protons are passing through an aluminum exit window (thickness 55 μm, diameter 16 mm) into the air. The energies of extracted proton beams are in the range from 6 to 37 MeV with the maximal current reaching several tens of microampere.

The positive mode allows acceleration of positive ions H^+, D^+, $^3He^{2+}$, and $^4He^{2+}$. In this case, the beam extraction is based on a system of electrostatic deflectors. The installation of the deflectors in the cyclotron vacuum chamber and the consequent evacuation takes approximately 24 h. This is a time consuming procedure. It requires conditioning of high voltage on the deflectors, tuning the beam extraction procedure, and setting of beamline elements. The extraction efficiency of the deflection system is limited by substantial beam losses occurring on electrodes of the deflectors. Typically, these irradiation conditions are operated during one week long campaigns about four times a year, in particular for nuclear astrophysics research and accelerating usually $^3He^{2+}$ beams which are nowadays rarely available.

Cyclotron operating in the negative mode allows for the production of medical radionuclides [20]. Morning transportation of radiopharmaceuticals to hospitals requires evening/night production runs, leaving ample time for research-oriented studies during daytime. Radiation hardness studies for the ALICE ITS upgrade project are carried out using the negative mode.

3.1. Time structure of the cyclotron beam

The cyclotron radiofrequency (RF) system is not operated at the continuous wave regime. In order to protect the RF accelerating system against discharges and to control the beam current, the RF frequency is modulated by a dedicated 150 Hz macropulsed signal. A duty cycle of the corresponding 6.67 ms signal period is adjustable and determines a time interval in-between the macropulses filled with proton microbunches. For the lowest RF used (≈10 MHz), the duty cycle can reach rather high values of about 65%. On the other hand, for the highest RF (≈25 MHz) the maximum duty cycle is limited to 25%. An example of a typical beam time structure is shown in Fig. 1. The duty cycle is therefore an important experimental parameter to be taken into account for on-line radiation hardness studies of detectors with fast response, e.g. the ALPIDE chip with a shaping time of about 2 μs.

[1] The operation of the isochronous cyclotron U-120M is supported by the Ministry of Education, Youth and Sports of the Czech Republic through the dedicated grant CANAM (Center of Accelerators and Nuclear Analytical Methods), which offers a unique open access to experimental infrastructure in nuclear physics and neutron science to scientists and industry [17].

3.2. Beam parameters

The maximal proton flux that can be reached in the negative mode is in the order of 10^{14} proton cm^{-2} s^{-1}. Such high current can be used to irradiate passive devices to produce material damage but it is too high for radiation testing of electronics like silicon sensors or field programmable gate arrays (FPGAs). Radiation hardness studies of electronics for the ITS upgrade project to be realized in a reasonable time period (hours) require fluxes which are in the order of 10^8 proton cm^{-2} s^{-1} or even a few orders of magnitude lower. The proton beam intensity provided by the U-120M cyclotron can be decreased by several methods:

1. lowering the arc current in the ion source,[2]
2. reducing the duty cycle,
3. increasing the gas pressure in the ion source,
4. shifting the horizontal position of the ion source extraction slit with respect to the slit of the puller electrode on the dee,
5. worsening the vacuum quality in the cyclotron vacuum chamber,
6. stopping a part of the beam on an integral beam probe at the final beam orbit in the vacuum chamber,
7. collimating extracted beam on a vertical input slit of the beamline.

The first three options have the advantage that they do not affect the beam position and profile. A common feature of the other options is that they decrease efficiency of the beam acceleration and extraction. By combining the above mentioned methods, proton flux at the beamline exit window can be lowered to $\approx 10^3$ proton cm^{-2} s^{-1}.

It is possible to decrease further the proton beam intensity by defocusing by the quadrupoles or in an extreme case by turning them off. This results in reducing the proton flux by approximately another order of magnitude. However, a major fraction of the divergent proton beam hits the internal surface of the beamline pipe and installed beamline elements. This approach can be used only for very low proton beam currents to avoid heat damages of the accelerator components. Moreover, when running in this mode, the beam trajectory has to be constrained by a beamline collimator to avoid the beam to be dominated by protons with energy up to a few MeV on average lower due to rescattering on the beamline pipe walls.

The beam energy is determined using three radially movable integral probes which measure an extracted orbit's center and radius. Based on these measurements, the energy of the beam is calculated by the unique mathematical model [21] of the cyclotron. Using this model and detailed simulations, the energy spread for 34.8 MeV was estimated to have an RMS of about 100 keV.

Although the U-120M is a variable energy cyclotron, the procedure of changing the beam energy takes about 20 min and includes a readjustment of cyclotron parameters such as the RF frequency, magnetic field, and beam trajectory corrections in the beamline. The time necessary for this tuning may take a rather significant portion of the total operation time, particularly when doing beam energy scans. To reduce this time, a remotely controlled energy degrader, which serves also as a fast beam stop, was constructed and installed. The energy degrader is mounted at the end of the beamline and allows to perform automated beam interruptions and energy scans without the need to touch the adjusted cyclotron settings. The cyclotron can then be operated under stable conditions during the whole irradiation. In this regime, long term beam intensity variations are below 10%.

[2] The cyclotron uses an internal cold cathode Penning type ion source. Ions from the source are extracted through a small slit by an extracting RF potential which is applied by a puller electrode. The puller electrode has a form of a tip on the dee electrode. It has a slit through which the ions enter the cyclotron vacuum chamber where they are accelerated. A scheme of the ion source and puller electrode arrangement in the central region of the cyclotron can be seen in Fig. 1 of [21].