A facility for radiation hardness studies based on the Bern medical cyclotron

J. Anders\textsuperscript{a}, S. Braccini\textsuperscript{a}, T. Carzaniga\textsuperscript{a}, A. Ereditato\textsuperscript{a}, A. Fehr\textsuperscript{a}, F. Meloni\textsuperscript{a}, C. Merlassino\textsuperscript{a}, A. Miucci\textsuperscript{a}, M. Rimoldi\textsuperscript{a} and M. Weber\textsuperscript{a}

\textsuperscript{a} AEC/LHEP, Universität Bern

March 7, 2018

The development of instrumentation to be operated in high-radiation environments is one of the main challenges in fundamental research. Besides space and nuclear applications, particle physics experiments also need radiation-hard devices. The focus of this paper is a new irradiation facility based on the medical cyclotron located at the Bern University Hospital (Inselspital), which is used as a controlled 18 MeV proton source. The adjustable beam current allows for dose rate dependent characterisation over a large dynamic range, from 0.1 to 1000 Grad per hour. The beam can be tuned so that the user can obtain the desired irradiation conditions. A complete study of the device under irradiation is possible thanks to dedicated beam monitoring systems as well as a power control system for the device under irradiation, which can be operated on-line. Further characterisations of the irradiated devices are possible thanks to a laboratory equipped with gamma spectroscopy detectors, ammeters and transient current technique setups.

1 Introduction

A medical cyclotron is in operation at the Bern University Hospital (Inselspital). It is a commercial IBA18/18 cyclotron, accelerating $H^-$ to 18 MeV \cite{1}. The machine is equipped with an external 6.5 m long beam transfer line which delivers the beam in a second bunker, referred as irradiation bunker in this paper. This feature makes it possible to conduct routine radio isotope production for PET diagnostics in parallel with multidisciplinary research activities. The Bern Cyclotron can be operated for research activities during the day time while radio isotope production for medical purpose is running over-night. The research program at the Bern Cyclotron includes the production and characterisation of radio-isotopes, the development of beam-monitoring detectors, and the characterisation of radiation-tolerant devices. The last issue is the subject of this paper. Radiation tolerant devices are fundamental in high-energy physics, space, nuclear and medical applications. In order to use a medical cyclotron for irradiation purposes a tuning and characterisation campaign was done, in particular the beam energy profile was measured and the cyclotron was tuned for low output current operation. It is fundamental to have an accurate dose measurement so that an beam monitoring setup was developed to provide a precise measurement of the output current. As a results of these studies the Bern Cyclotron allows for an accurate adjustment of the beam current, in this way it is possible to make real-time studies on the device under irradiation. It is hence possible to obtain different radiation conditions or allow dose rate dependent characterisation. The Bern Cyclotron allows for radiation hardness studies with a lower limit of the dose at $\sim$ 10 krad. The facility is fully equipped to host custom readout of the device during the irradiation. Temperature control of the device is possible with Peltier elements and/or water cooling. A dedicated laboratory is available
Figure 1. Diagram of the cyclotron facility, the cyclotron bunker is separated from the irradiation bunker where the irradiation apparatus sits. This facilitates the access to the device under irradiation due to the low level of activity in the irradiation bunker, below 2 µSv per hour.

on-site equipped with germanium and scintillating detectors for measuring the samples emission spectrum and activity. A high performance ammeter for electrical measurement is also available. Further characterisation is possible in the nearby Laboratory for High energy Physics (LHEP) thanks to transient current technique setups, FPGA custom logic setups for electronic device characterisation and high-voltage power supplies for the current-voltage characterisation.

2 The Bern cyclotron and its beam transport line

The Bern Cyclotron is an IBA Cyclone 18 MeV cyclotron which is equipped with two $H^-$ sources. It can provide beam currents up to 150 µA in single or dual beam modes. This current is never reached in a typical irradiation and it is limited to few hundred nA output. Proton extraction is achieved by stripping off the electrons from the negative $H^-$ ions with 5 µm thick pyrolytic carbon foils. A detailed description of the Bern cyclotron can be found in Ref. [1]. The beam is transported to the irradiation bunker with an transfer efficiency of greater than 95% via a 6.5 m long beam transfer line (BTL). The research bunker has a low level of activity, below 2 µSv per hour, allowing access to the beam area. The irradiation bunker can be then accessed a few minutes after the beam is switched off, making intervention possible. For this reason an irradiation facility was setup there as shown in Figure 1. The accelerated protons are steered by an X-Y magnet system and are directed towards a collimator. The focusing of the beam is realised using two horizontal-vertical quadrupole doublets; the first is located in
the cyclotron bunker and the second in the irradiation bunker. A 1.8 m thick wall divides the bunkers and is necessary to stop the fast neutron flux generated during isotope production. For the same reason, a movable cylindrical neutron shutter is located inside the beam pipe while the beam transfer line is not in use. Two beam viewers are present in the line allowing for beam current measurements. Despite the design of the cyclotron for high current operation (with maximum of 150 μA), operation with currents at the pA level is possible. A dedicated tuning was performed for this purpose. This is not a standard setting for commercial cyclotrons and, as a result, additional developments were required. A detailed description of the tuning process can be found in Ref. [2]. Optimised settings were obtained for the operation of the ion source, the main coil, the radio-frequency systems and for the BTL magnets.

3 The dose measurement method

The measurement of the dose is essential to link the evolution of the device performance to the bulk and surface damages caused by the radiation. A proton beam interacts with the material by means of ionisation and nuclear processes. It is important to measure the absorbed dose due to the two different components, which are both proportional to the flux of protons hitting the device. The dose due to ionisation ($D_{ion}$) and nuclear ($D_{nuc}$) processes can be calculated with Eq. 3.1:

$$D = \phi \cdot \frac{1}{\rho} \left( \frac{dE}{dx_{ion}} + \frac{dE}{dx_{nuc}} \right) = D_{ion} + D_{nuc};$$

where $\phi$ is the fluence, defined as number of incident particles per unit area, $\rho$ the density of the target and $\frac{dE}{dx_{ion/nuc}}$ is the average energy loss per unit of length in a given material for either ionisation or nuclear interactions. The effects of nuclear interaction are often compared to a reference 1 MeV neutron fluence as can be seen in Eq. 3.2

$$\phi(1 \text{ MeV } n_{eq}) = \int_0^{+\infty} D(E)\phi(E)dE \frac{D_{1\text{MeV } n_{eq}}}{D_{1\text{MeV } n_{eq}}}.$$  

where $\phi(E)$ is the fluence of certain kind of particles at a given energy E and D is the damage function which depends upon the target material, the characteristics of the incident particle (energy, mass and electrical charge). The measurement of the fluence is used to assess the dose, for both nuclear and ionising phenomena, if the proton energy and the material properties are known. The fluence can be obtained by measuring the beam current:

$$\phi = \int_{t_0}^{t_1} \frac{j(t)}{Q_e} dt;$$  

where $j(t)$ is the current per unit area, $Q_e$ is the charge of the proton and $[t_0, t_1]$ is the time interval of the irradiation. A measurement of the current per unit area during the irradiation allows to measure the dose rate and at the same time to have a complete history of the irradiation. In particular, the dose rate measurement is relevant for identifying non-linear phenomena which are typical in electronics, as presented in Ref. [3].

4 The irradiation setup

A dedicated irradiation setup was developed for the measurement of $j(t)$. The method relies on the extraction of the central part of the beam to irradiate the device, while dumping the outermost part of the beam for measuring the current density. It is important to operate the cyclotron so that the delivered beam has a constant intensity per
unit surface in the transverse plane. The transverse uniformity guarantees a uniform irradiation of the device and as well as a constant beam density over the dump area. In order to obtain the required beam profile, the downstream quadrupole doublets of the BTL are switched off. In this way the beam profile is flat to within 20% up to 40 mm in both the vertical and the horizontal directions. The irradiation setup is shown in Fig. 2. It is composed of two detectors: a two-dimensional beam profile detector and a collimator to measure the density current and to extract the beam with a custom profile. The extraction window consists in a 300 μm thick aluminum layer. A 2D movable stage completes the system, allowing for the irradiation of large surface devices, up to $30 \times 30$ cm$^2$, or the irradiation of several devices without accessing the irradiation bunker. The 2D-stage has a 10 μm precision, more details can be found in Ref. [4].

The two-dimensional beam profiler is a prototype detector developed at University of Bern which consists of a matrix of silicon dioxide enriched with ytterbium [5, 6]. Protons hitting the matrix produce fluorescence in ytterbium. The matrix is placed at an angle of 45° to the beam and the fluorescence is monitored by a National Instrument Smart Camera [7]. Further processing is performed to obtain the final bi-dimensional and one-dimensional profiles. A 2d image of the beam is shown in Fig. 3. A paper describing the detector is in preparation. The system was calibrated and aligned with the UniBeam detector [8].
Figure 3. Beam shape obtained with the two-dimensional beam profiler. The colour scale is in arbitrary units. The dark dots in the picture are due to a poor ytterbium deposition on the device. The beam is flat to within 20%. A correction factor $\Lambda$ is derived to take into account this non-homogeneous transverse profile.

The current density is measured with a dedicated collimator, developed at the University of Bern. The cross-section of such collimator is shown in Fig. 4. It consists of three aluminum rings: the shaping ring, the high-voltage ring, and the beam dump. Each of the rings is 5 mm thick, this thickness was optimised considering that 18 MeV protons have a range of 1.6 mm in aluminum.

The proton beam coming from the BTL enters the system of collimators through a 40 mm diameter opening and is further shaped through the shaping ring of 35 mm inner diameter. After the shaping ring, the proton beam hits a dump ring, which also acts as collimator, allowing the beam to be extracted via a dedicated opening. Several versions of the dump ring are available, so that the beam can be extracted with different transverse shapes. Finally, the beam is extracted into air through a 300 $\mu$m aluminum window. The part of the beam absorbed by the beam dump is used for the current density measurement. The dump ring is electrically connected to a high precision ammeter (Keysight Ammeter b2985a[9]), which has a precision of 0.01 fA in the current measurement.

When the protons hit the aluminum surface of the beam dump, they extract secondary electrons. This phenomenon can lead to an overestimation of the current up to $\sim 20\%$ and it has been documented in Ref. [2]. In order to prevent this to happen, the system is biased with high-voltage. In particular an intermediate high voltage ring is then placed between the shaping ring and the dump ring. The high-voltage ring has an inner diameter of 37.5 mm and is biased at $-100$ V, preventing the extraction of secondary electrons in the dump ring. The bias voltage is provided by an ammeter.

The entire system is operated in vacuum in order to prevent air ionisation. This is necessary to avoid the beam to produce electrons which would be collected at the dump affecting the current measurement. For this
Figure 4. Cross section of the collimator system. The proton beam coming from the cyclotron enters the collimators system through an opening circular window of 40 mm. The beam is reduced to 35 mm diameter by means of a shaping ring. At this stage a flat beam of 35 mm diameter approaches the dump ring. This acts as a collimator, so that part of the beam is extracted and delivered to the device under test through an aluminum extraction window, 300 µm thick. The rest of the beam is absorbed on the dump ring so that the current density is measured. When hitting the dump rings, the protons produce secondary electrons at the aluminum surface. For this reason a high voltage ring is in between the shaping ring and the dump ring. A bias voltage of −100 V is applied, so that the electrons are pushed back to the dump ring.

reason the system is kept at ∼ 10⁻⁸ bar, the vacuum system is the one provided by the BTL. External services are provided with two feedthrough connections: one devoted to a high voltage supply, and the other to connect the ammeter to the beam dump layer.

The current per unit area \( j(t) \) is calculated according to Eq. 4.1:

\[
j(t) = \frac{i(t)}{A_{BD}} \cdot \Lambda; \tag{4.1}
\]

\[
A_{BD} = \pi \cdot r^2 - A_{\text{open}} = 9.62 \text{ cm}^2 - A_{\text{open}}; \tag{4.2}
\]

\[
\Lambda = \frac{\rho_{\text{extraction}}}{\rho_{\text{dump}}}. \tag{4.3}
\]
Figure 5. Distribution of the proton energy. The square points are the measured beam profile fitted with the Verhulst function before the extraction window. The effect of 300\,\mu\text{m} aluminum extraction window has been simulated and it is shown by the open circle points. A dedicated Monte Carlo simulation was performed based on SRIM tables.

The current measured at the dump ring \(i(t)\) is divided by the enlightened surface area \(A_{BD}\) and corrected for beam inhomogeneities. The area \(A_{BD}\) is calculated in Eq. 4.2 and it depends on \(A_{open}\), which is the extraction area. A correction factor \(\Lambda\) takes in account the measurement of the two-dimensional beam profile. It is calculated as in Eq. 4.3, where \(\rho_{extraction}\) is the beam density at the extraction area and \(\rho_{dump}\) the one at the dump ring surface.

5 The beam stopping power

The current per unit area is not the only parameter to be taken in account for the dose measurement. Eq. 3.1 shows that the stopping power \(\frac{1}{\rho} \frac{dE}{dx}\) needs to be known. The stopping power depends on the beam energy and the material of the device under irradiation. The beam energy of the Bern Cyclotron was measured to be 18.3 ± 0.4 MeV [10]. The Bern Cyclotron beam energy distribution is shown by the square points in Fig. 5 which has been fitted with a Verhulst function shown by the red curve. The additional aluminum thickness of 300\,\mu\text{m} of the extraction window needs to be taken in account. A Monte Carlo simulation was performed, based on SRIM 2013 [11] tables, to derive the beam energy probability density function after the extraction window, represented by the blue circles in Fig. 5. A fit was performed with a Verhulst function convoluted with a gaussian, the mean energy was estimated to be 16.7 ± 0.5 MeV after the extraction window.

Table 1 shows the stopping power and the hardness factor for several materials considering a 16.7 MeV proton beam. The dose profile needs to be calculated depending on the material on the device under irradiation and its thickness. For example the protons will lose \(\sim 0.55\) MeV in the first 100\,\mu\text{m} in silicon.
Table 1. Stopping power for different material in case of proton beam of 16.7 MeV. The values are obtained from the NIST database.

| Material                        | $\frac{1}{\rho} \frac{dE}{dx_{ion}}$ [MeV cm$^2$ g$^{-1}$] | $\frac{1}{\rho} \frac{dE}{dx_{nuc}}$ [MeV cm$^2$ g$^{-1}$] |
|---------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| Silicon                         | 23.25                                                       | 0.011                                                       |
| Silicon dioxide                 | 24.31                                                       | 0.012                                                       |
| Aluminum                        | 22.67                                                       | 0.011                                                       |
| Plastic scintillator (Vyniltoluene) | 30.12                                                       | 0.015                                                       |
| Mylar                           | 28.06                                                       | 0.013                                                       |
| Photographic emulsion           | 18.30                                                       | 0.009                                                       |

Figure 6. Observed beam current during an irradiation with the estimated delivered dose given a test silicon device

6 Performance and calibration of the irradiation setup

Figure 6 shows the beam current intercepted by the dump ring and the dose measured during a typical irradiation taken as an example. The blue curve represents the dose, where the light blue error bar takes in consideration a 5% uncertainty on the stopping power value and 500 µm uncertainty on the acceptance radius of the dump ring. The experimental uncertainty on the current was measured to be negligible. The final uncertainty on the dose determination was estimated to be 6% of the dose value. A stability of approximatively 20% of the beam current can be achieved by the operator with a manual adjustment of the beam. A software for online beam monitoring has been developed to provide the current and the dose measurement in real time. Data are updated every 250 ms. Figure 6 shows data-taking example from irradiation that took place to evaluate the performance of the cyclotron. In the first 140 s the beam current is increasing. This behavior was driven by the cyclotron operator, because the user wanted to observe the effects on the device due to an increasing beam current. After 200 s the current is constant within 5% and the beam parameters were kept constant until the end of the irradiation. The beam was shut down temporarily in 2 occasions because of user request.
Figure 7. Comparison between the film calibration provided by Far West Technologies and the dose measurement at the Bern Cyclotron. The two measurements techniques are compatible within 15% as showed by the ratio in the bottom of the plot.

To check the assessment of the delivered dose, measurements were performed with radiochromic films. The film is positioned between the extraction window and the sample under irradiation. This measurement is available only at the end of the irradiation and is used as a cross-check of the delivered dose and the uniformity of the irradiation at the extraction of the beam. The radiochromic films used are FWT-60 made by Far West Technology (FWT) [? ]. They are made of hexa(hydroxyethyl) aminotriphenylacetonitrile (HHEVC) dyes, and are available in different thickness: 10 µm and 47 µm. Fig. 7 shows the film calibration performed by FWT in the top plot with black squared points; the red round points show the measurement performed at the Bern Cyclotron where the dose is measured with the method described in Sections 3 and 4. The measurements of the optical absorbance followed the prescription by FWT. The bottom plot shows the ratio of the dose measurement with Bern setup and the one provided by FWT at the same optical absorbance. This value is shown for the different dose measurements done with the Bern setup. In order to minimise the uncertainty on the optical absorbance several films were irradiated in independent measurements. The uncertainty on the measured optical absorbance takes into account an uncertainty of 5 µm on the film thickness, as indicated by the FWT. The uncertainty of the dose measured in Bern follows the same consideration done for Fig. 6 where the stopping power for a proton beam of 16.7 MeV in HHEVC was calculated to be 30.87 MeV · cm²·g⁻¹ with a dedicated SRIM simulation.
7 Conclusions

An irradiation facility is in operation at the Bern Medical Cyclotron using the 18 MeV proton beam. Given the high precision control of the beam current and the online beam monitoring system, it is possible to have an online measurement of the total delivered dose, for both ionising and non-ionising phenomena. A dedicated system was developed for current monitoring during the irradiations, providing measurement of the total beam intensity and as well as the beam profile. A dose measurement technique was developed by the measurement of the beam current. The method was checked with pre-calibrated radio-chromic films and the two techniques have been found to be compatible within 15%. The maximum area of the extracted beam is a square of $2 \times 2 \text{cm}^2$. Thanks to a downstream 2D-stage irradiation of samples of larger area is possible with multiple steps. The irradiation facility is able to deliver from $0.1 \text{Mrad h}^{-1}$ to $1 \text{Grad h}^{-1}$ thanks to adjustable beam current from few pA to few hundreds nA. A laboratory for sample characterisation is available on site for further measurements of the irradiated samples. Two high-purity germanium detectors are available to check the isotope composition of the sample before and after irradiation. Electrical measurements can be performed with a precision ammeter, capable of measuring current down to 0.01 fA. Further characterisation of the device under irradiation can be done with multi-channel low voltage power supplies available in-site. Cold storage of the irradiated samples is possible under request. A transition-current-technique setup is also available for characterisation of the bulk properties for solid-state detectors. The Bern Cyclotron has, up to now, hosted different irradiation campaigns for high-energy physics experiments, such as ATLAS and LHCb, and as well as for astro-physics and medical-physics studies.

References

[1] S. Braccini, The new bern PET cyclotron, its research beam line, and the development of an innovative beam monitor detector, in American Institute of Physics Conference Series, F. D. McDaniel, B. L. Doyle, G. A. Glass, and Y. Wang, eds., pp., 144–150. Apr., 2013.

[2] M. Auger, S. Braccini, A. Ereditato, K. P. Nesteruk, and P. Scampoli, Low current performance of the Bern medical cyclotron down to the pA range, Measurement Science and Technology 26 no. 9, (2015) 094006. http://stacks.iop.org/0957-0233/26/i=9/a=094006.

[3] ATLAS Collaboration, Irradiation induced effects in the FE-I4 front-end chip of the ATLAS IBL detector, pp., 1–4. 2016. arXiv:1611.00803 [physics.ins-det].

[4] “Intellidrives.” http://www.intellidrives.com/XY-tables-XYZ-Systems/XY-Tables/XY-Table-BSMA-LY-140H-300x300.

[5] M. Schefer, Study of a novel two-dimensional online beam monitoring detector, bachelor thesis, University of Bern, February, 2018. Supervisor: Saverio Braccini.

[6] M. Schmid, Development and Optimization of a Two-Dimensional Beam Monitoring Detector at the Bern Medical Cyclotron Laboratory, bachelor thesis, University of Bern, February, 2018. Supervisor: Saverio Braccini.

[7] “Smart camera.” http://www.ni.com/it-it/shop/select/smart-camera.

[8] M. A. et al., A detector based on silica fibers for ion beam monitoring in a wide current range, JINST 11 P03027 (2016).

[9] “Keysight b2980 series.” https://literature.cdn.keysight.com/litweb/pdf/5991-4878EN.pdf?id=2500920. Accessed: 2010-09-30.

[10] K. P. Nesteruk, M. Auger, S. Braccini, T. S. Carzaniga, A. Ereditato, and P. Scampoli, A system for online beam emittance measurements and proton beam characterization, arXiv:1705.07486 [physics.acc-ph].
[11] J. F. Ziegler, M. D. Ziegler, and J. P. Biersack, *SRIM - The stopping and range of ions in matter (2010)*, *Nuclear Instruments and Methods in Physics Research B* **268** (2010) 1818–1823.