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### Recent results and experience with the Birmingham MC40 irradiation facility

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## Recent Results and Experience with the Birmingham MC40 Irradiation Facility

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**ABSTRACT:** Operational experience with the recently upgraded irradiation facility at the University of Birmingham is presented. This is based around the high intensity area of the MC40 medical cyclotron providing proton energies between 3 and 38 MeV and currents ranging from tens of fA to  $\mu$ A. Accurate dosimetry for displacement damage and total ionizing dose, using a combination of techniques, is offered. Irradiations are carried out in a temperature controlled chamber that can be scanned through the beam, with the possibility for the devices to be biased, clocked, and read-out. Fluence up to several  $10^{16}$  1 MeV  $n_{eq}/cm^2$  and GRad ionizing dose can be delivered within a day.

**KEYWORDS:** Detector design and construction technologies and materials, Radiation-hard detectors, Solid state detectors, Radiation damage to detector materials (solid state)

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## 1 Introduction

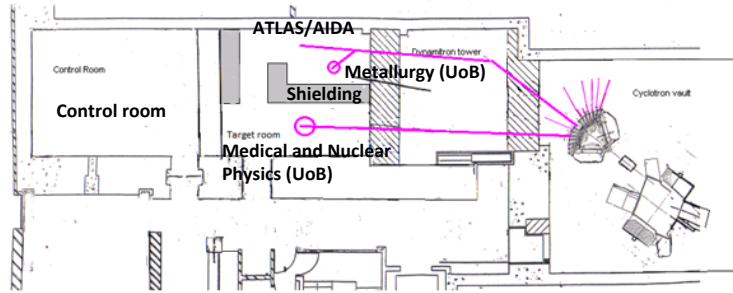
From particle physics experiments to space and material applications there is an ever increasing need for sensors and components with enhanced tolerance to radiation. The high intensity area of the MC40 medical cyclotron at the University of Birmingham offers the possibility for testing such technologies. Fluence up to several  $10^{16}$   $n_{eq}/cm^2$  and GRad ionizing dose can be delivered within a day. The facility [1, 2], a part of the AIDA-2020 framework for transnational facility access, is already being used intensively to irradiate silicon sensors, microelectronics and integrated circuits, optical components, and mechanical structures for the LHC upgrade programme and beyond.

The overview of the irradiation facility is presented in Sec. 2, followed by the description of the configuration used during irradiation in Sec. 3. The commissioning of the facility is discussed in Sec. 5 and the dosimetry in Sec. 4. Finally, the summary and conclusions are presented in Sec. 6.

## 2 Irradiation facility

The MC40 medical cyclotron is the third cyclotron to be operated at the University of Birmingham, following the 60” Nuffield cyclotron (1948-1999) and the radial ridge cyclotron (1960 - 2002). The cyclotron, which was transferred to Birmingham from the Minneapolis Veteran Hospital, started operations in 2004. It is primarily used for radio-isotope production, mainly for medical applications. It provides, practically, continuous beams of various particle species in a range of kinetic energies: protons in the ranges 3 – 9 and 11 – 38 MeV, deuterons between 5.5 and 19 MeV,  $^3\text{He}$  ions in the ranges 9 – 27 and 35 – 53 MeV, and  $^4\text{He}$  ions between 11 and 37 MeV.

The cyclotron is equipped with a 12-way switching magnet, that allows the extraction of the beam in several lines. Initially, one beam-line ran into a room adjacent to the cyclotron vault to offer the possibility for study of radiation effects, e.g. on electronics for space applications. A second beam-line extending into a specially shielded area was constructed in 2013, as shown in Fig. 1, which allowed high dose-rate radiation damage studies. This upgrade was performed to accommodate the



**Figure 1.** Layout (not to scale) of the irradiation facility of the University of Birmingham, featuring the cyclotron vault, the high intensity irradiation area, and the operator control room.

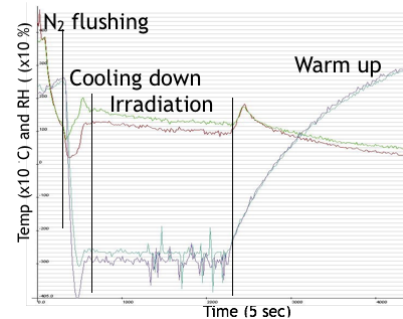
needs for radiation damage studies for the ATLAS upgrade for the High Luminosity LHC; around 300 samples have been irradiated to-date. The proton current in this area can be increased up to  $2 \mu\text{A}$  in a beam spot, typically, of about  $10 \times 10 \text{ mm}^2$ , reaching a flux of  $10^{13}$  protons/s/cm<sup>2</sup>. As a rule of thumb, the facility can deliver fluences of  $10^{15}$  1 MeV  $n_{\text{eq}}$ /cm<sup>2</sup> in 80 s at  $1 \mu\text{A}$ . This is the fluence that silicon strip sensors need to withstand at  $3000 \text{ fb}^{-1}$  at the High Luminosity LHC [3]. Typically, proton energy of 27 MeV and current of  $0.1 - 0.5 \mu\text{A}$  are used during irradiations. The beam current is monitored in real-time with a Faraday cup.

### 3 Irradiation setup

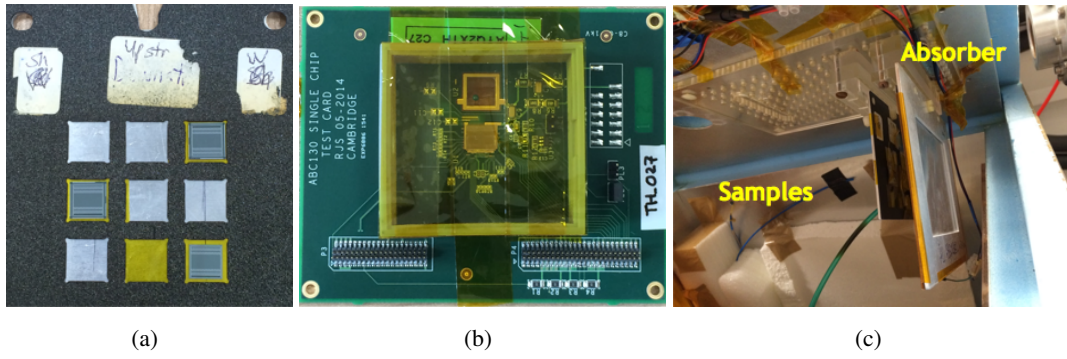
During irradiation, the samples are placed in a temperature controlled chamber with a  $150 \times 150 \text{ mm}^2$  window on each side to allow beam entry and exit. A feed-through allows external biasing, clocking, read-out, and monitoring of the irradiated components.

A Norhof liquid nitrogen evaporative cooling system is used for cooling the chamber. Typically, irradiations are taking place at temperatures of  $-25^\circ\text{C}$ , while temperatures down to  $-50^\circ\text{C}$  have been successfully achieved and sustained. Nitrogen gas flows in the chamber to control humidity, with typical relative humidity values of about 10% achieved during irradiation, while sufficient air circulation is ensured with electric fans. The temperature and humidity are monitored with three temperature and two humidity sensors, placed at different locations in the chamber and logged with an Arduino-Uno system. The environmental conditions for irradiation are achieved within about 40 minutes, as shown in Fig. 2.

Depending on the sample under irradiation, different approaches are employed for mounting and securing it in the chamber. Semiconductor sensors are mounted with kapton tape on carbon fibre frames, which are available at predetermined dimensions to fit bare sensors, as shown in Fig. 3(a). For integrated circuits on a printed circuit board a



**Figure 2.** Temperature and relative humidity monitoring in the temperature control chamber, where the various stages are shown: nitrogen flushing, cooling, irradiation, and warming-up. The abrupt fluctuations during irradiation are due to interference from the scanning table motors.



**Figure 3.** Samples to-be-irradiated ready for mounting in the temperature controlled chamber: (a) silicon sensors mounted with kapton tape on a carbon fibre frame; and (b) integrated circuit on printed circuit board, the wire bonds are protected by means of a 3D-printed frame. (c) The irradiation-ready samples suspended from the lid of the temperature controlled chamber. Seen also is the 300  $\mu\text{m}$  aluminium absorber, discussed in Sec. 5.

3D-printed frame is used to protect the wire bonds, as shown in Fig. 3(b). The frames are then mounted on an aluminium plate, which is suspended from the chamber lid, as shown in Fig. 3(c). Appropriately shaped nickel foils are placed in front of the samples to measure the fluence.



**Figure 4.** The temperature controlled chamber, the beam line with beam direction indicated, and the Faraday cup at the setup.

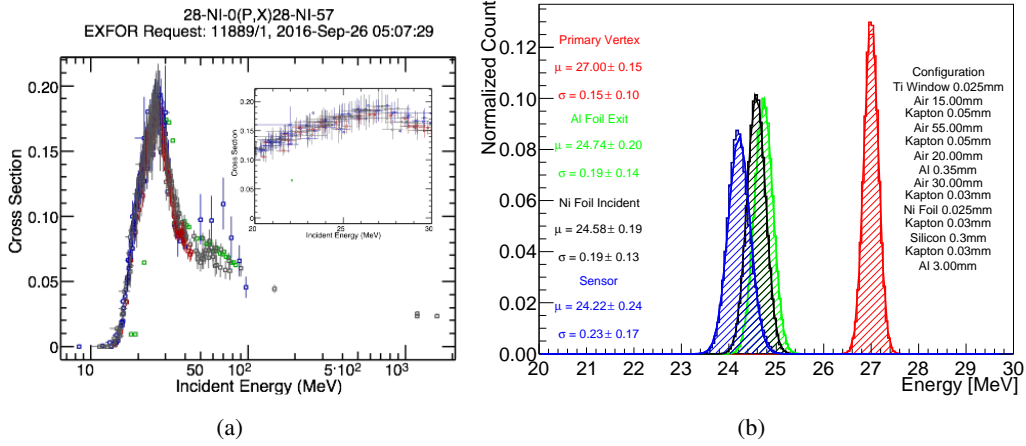
The chamber is mounted on a XY-axis robotic scanning system [4]. The scanning system, whose main parameters are summarised in Table 1, is operated via a custom-made LabVIEW graphical user interface. Two modes of operation are available: a) Scanning; where the chamber follows a user specified path, typically in horizontal rows with a vertical step of 5 mm; and b) Point-to-point; where the position of the chamber is fixed during irradiation. The former is less susceptible to beam non-uniformities than the latter, which is relevant for samples smaller than the beam spot. The arrangement of the various elements in the irradiation area is shown in Fig. 4. Prior to irradiation the beam position and profile are obtained by exposing Gafchromic film to the beam.

	Horizontal	Vertical
Stroke	450 mm	400 mm
Speed	0.8 – 20 mm/s	19 mm/s
Accuracy	$\pm 50 \mu\text{m}$	$\pm 200 \mu\text{m}$

**Table 1.** Scanning system operation parameters. A National Instruments CompactRIO Real-Time programmable controller is used for the precision horizontal axis and a third party servomechanism for the vertical axis.

## 4 Dosimetry

The fluence delivered on the irradiated samples is estimated offline using the nickel foils placed in front of the sample during irradiation. During irradiation with protons the isotope  $^{57}\text{Ni}$  is created which subsequently decays through  $\beta^+$  decay to  $^{57}\text{Co}$ . The activity of the isotope is measured with a high-purity germanium spectrometer through the 1.378 MeV line, which has an intensity of 81.7% [5]. The cross-section for the  $^{57}\text{Ni}$  production depends on the proton beam energy, as shown in Fig. 5(a). A Geant4-based [6] simulation is used to determine the beam energy at different locations between the collimator and the sample. As shown in Fig. 5(b), for an initial 27 MeV kinetic energy at extraction, the protons impinge on the nickel foil and the sample with an energy of 24.6 and 24.2 MeV, respectively. The measured and target fluence agree within 10%. A measurement of the hardness factor for the protons provided by the facility obtained by irradiating BPW34F commercial p-i-n diodes [7] and comparing with measurements from Ref. [8, 9], is currently underway.



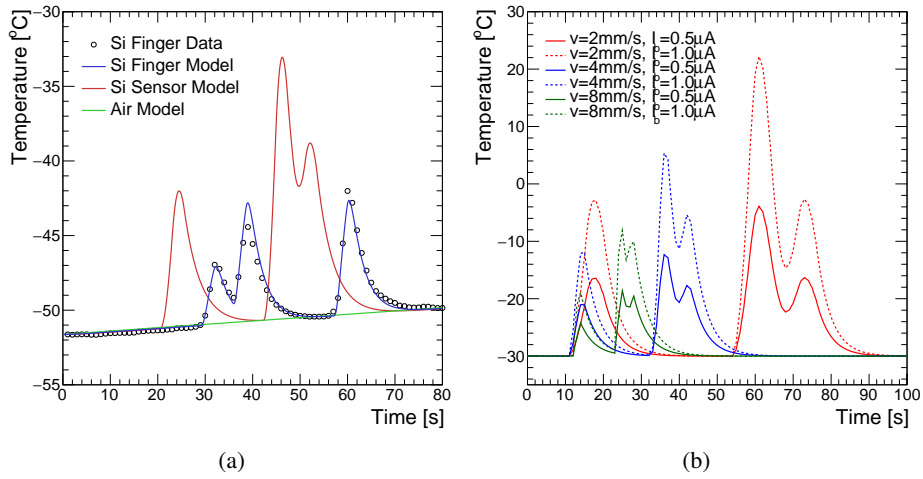
**Figure 5.** (a) Production cross section of the  $^{57}\text{Ni}$  isotope during irradiation with protons of various energies. Data from Ref. [10]. (b) Simulated proton energy distribution at various points in the irradiation setup.

## 5 Commissioning of the facility

At the early stages of the commissioning of the facility issues were observed, as a result of thermal annealing of the sensors during irradiation. Action was taken to upgrade the cooling system from a glycol-based system, operated between  $-15$  and  $-25^\circ\text{C}$  depending on heat load, to the current system using liquid nitrogen [11].

Furthermore, detailed studies on the silicon sensor temperature during irradiation, as a function of the beam current and the scanning velocity, were undertaken. The sensor temperature cannot be measured directly during irradiation, as the attached temperature sensor would be also irradiated. Therefore, a thin “finger” of silicon otherwise identical to the sensor has been deployed. The temperature sensor is glued with silver loaded epoxy at the edge of the finger, and thus away from the scanning beam. As presented in Fig. 6(a), the temperature measurements from the finger are extrapolated to obtain the temperature on the actual sensor during irradiation through a model





**Figure 6.** (a) Temperature measurements on the silicon finger, along with the fitted model, and the prediction for the silicon sensor. (b) Expected variation in temperature as a function of time during sensor irradiation for various scanning speeds and beam currents.

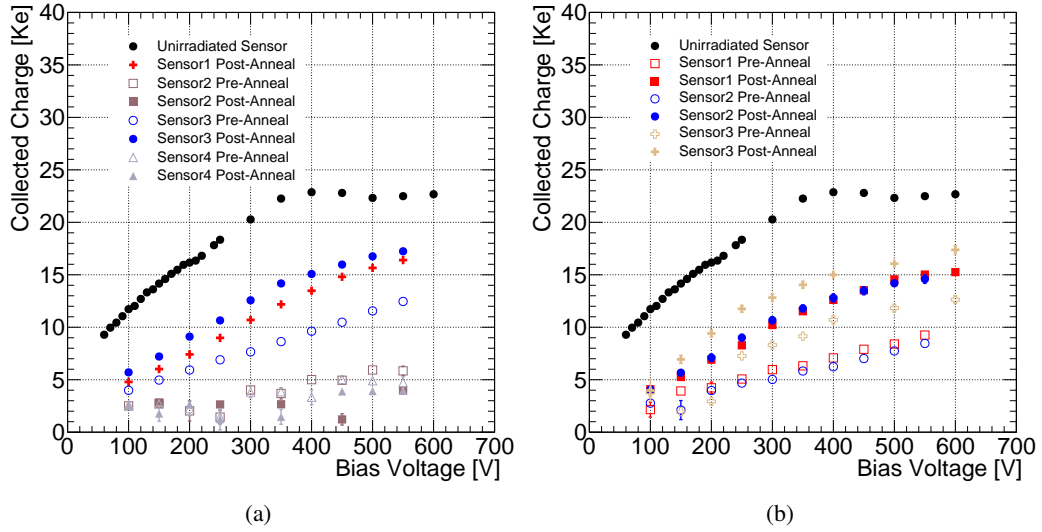
accounting for the heating due to the beam and cooling through convection to the environment of the chamber. The thermodynamical model was validated with laboratory measurements under various conditions of heat load, environmental temperature, and surrounding air-flow. Using these data and the associated model the temperature of the sensor as a function of time is estimated for various beam currents and scanning velocities, as shown in Fig 6(b). In each configuration the subsequent peaks in temperature correspond to the crossing of the sample through the beam. Finally, a beam current of up to  $0.5 \mu\text{A}$  at a scanning velocity of  $4 \text{ mm/s}$  was preferred.

Charge collection and current-voltage measurements were performed on  $1.0 \times 1.0 \text{ cm}^2$  silicon strip sensors prior and post irradiation with an ALIBAVA system [12]. Measurements were also performed after controlled thermal annealing by heating to  $60^\circ\text{C}$  for 80 min. Samples irradiated under the optimised conditions showed evidence of broad clusters, further reduction to signal following controlled thermal annealing, and reduced inter-strip isolation.

The initial hypothesis of an environmental issue inside the chamber was not supported: a sensor put through the same procedure, but not placed in the path of the beam, demonstrated no changes in its properties. A systematic set of measurements was obtained for various conditions of irradiation: placing  $300 \mu\text{m}$  aluminium absorber in front of the sensor, placing the sensor within a kapton enclosure, and placing the sensor behind a nickel foil. Combinations of the above were also tried, as shown in Table 2.

	Sensor 1	Sensor 2	Sensor 3	Sensor 4
kapton enclosure	✓	✓	✗	✗
Ni foils	✓	✗	✗	✗
$300 \mu\text{m}$ Al	✓	✗	✓	✗

**Table 2.** Configurations used during the systematic study of irradiation conditions.



**Figure 7.** (a) Charge collection measurements for sensors irradiated to  $5 \times 10^{14}$  MeV  $n_{eq}/cm^2$  in the configurations summarised in Table 2. (b) Charge collection measurements for sensors positioned behind 300  $\mu m$  of aluminium. Sensor 1 was irradiated to  $7 \times 10^{14}$  MeV  $n_{eq}/cm^2$  in point-to-point mode with beam current 100 nA. Sensors 2 and 3 were irradiated to 9 and  $10 \times 10^{14}$  MeV  $n_{eq}/cm^2$  in scanning mode with beam current 400 nA and scanning velocity 4 mm/s and 1 mm/s, respectively.

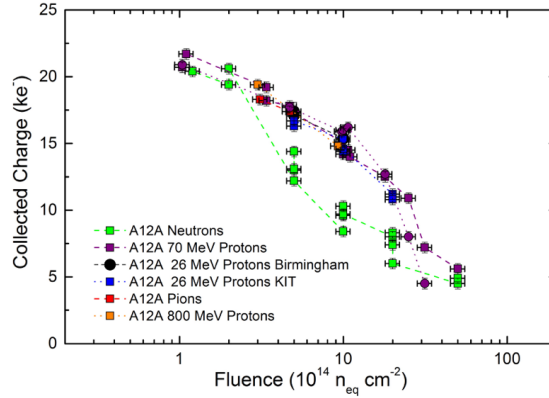
The results of the charge collection measurements are summarised in Fig. 7(a), for sensors exposed to  $5 \times 10^{14}$  MeV  $n_{eq}/cm^2$ . It is demonstrated that sensors placed behind 300  $\mu m$  of aluminium show the expected behaviour, while placing the sensors in a kapton enclosure, or behind a nickel foil had no significant effect. This finding points to a low energy component contaminating the beam, possibly through beam interaction with the collimator. Bragg peak and current measurements did not provide further insight on the source of this contamination.

Subsequently, sensors were placed behind 300  $\mu m$  of aluminium and were irradiated to  $10^{15}$  MeV  $n_{eq}/cm^2$  under various operation modes. The charge collection measurements, shown in Fig. 7(b), demonstrate the expected behaviour. The obtained results are compared to those from other facilities, for the same sensor type, in Fig. 8. The measurements for sensors irradiated at the Birmingham MC40 cyclotron are in good agreement with those obtained at other facilities and are compatible with the design parameters for High Luminosity LHC [13]. As a result, the facility is now commissioned and can be used for further radiation tolerance studies.

## 6 Conclusion

Upgrades to the Birmingham Irradiation Facility have been made with respect to the setup in [1, 2]. Irradiations of silicon sensors are carried out in a temperature controlled chamber at  $-25^\circ C$ , which is mounted on a robotic scanning system. Following a commissioning period, several measurements on ATLAS silicon strip sensors are in good agreement with reference measurements performed in other facilities. The facility, which is used to irradiate a diverse set of equipment, is now fully operational and can be used for further radiation tolerance studies.





**Figure 8.** Measurements of collected charge at 500 V for sensors irradiated at the University of Birmingham and other facilities. Comparison data reported in Ref. [13]

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