The Birmingham irradiation facility

Laura Gonella on behalf of the UK irradiation team

RD50 workshop, Torino

07/06/2106
Outline

- Overview of the irradiation facility
- Results from sensors irradiations
- Dosimetry
- Ongoing and future irradiation program
- Conclusion
The MC40 cyclotron at the University of Birmingham is primarily used for radioisotope production for mainly medical applications.

It was commissioned as an irradiation facility for particle physics in early 2013 and has irradiated around 300 samples in total.

Joint activity by the Universities of Birmingham, Liverpool and Sheffield through STFC support for UK ATLAS Upgrade.

The Birmingham Irradiation facility is an AIDA-2020 Transnational Access Facility.
The UK irradiation team

David Parker (AIDA-2020 Responsible)
Mike Smith
John Wilson
Kostas Nikolopoulos
Phil Allport (AIDA-2020 Contact)
Laura Gonella
Tony Price
Juergen Thomas
Daniel Briglin
James Broughton
Matt Baca

Paul Dervan (ATLAS-UK Irradiations)
Gianluigi Casse
Sven Wonsak

Richard French
Hector Marin-Reyes
Paul Hodgson
Kerry Parker
Evangelos Kouritis
Sam Edwards
Paul Kemp-Russell
Simon Dixon
- Proton energy at extraction: up to 40MeV
- Proton current: up to 2μA (cooling permitting)
- Beam spot: approx. $10\text{mm} \times 10\text{mm}$
- Flux: up to $10^{13}$ protons/s/cm$^2$

Typically:

$E_{\text{beam}} = 27\text{MeV}$

$l_{\text{beam}} = 0.1-0.5\mu\text{A}$
Irradiation setup

- Temperature controlled box mounted on XY-axis (45cm×40cm) scanning system allows areas of 15cm×15cm (orthogonal) to be uniformly irradiated at low temperatures
- Liquid nitrogen evaporative cooling system (‘Norhof LN2’). Typ. $T = -25^\circ C$ during irradiation
- Dry N2 is used to keep low humidity. Typ. RH = ~10% during irradiation
- Sealed feed-through allow external read-out and monitoring during irradiation
- Samples are suspended from the lid in the box
- **0.3mm aluminum absorber** in front of samples used to remove low energy components
- **Faraday cup** used to measure beam current
- **Carbon fiber frames** are available to predetermined dimensions to fit bare sensors
- Sensors are held in place with kapton tape
- For ASICs on PCB a 3D printed frame is used to protect the wire bonds
- Carbon frame with sensors/PCBs fixed to Al-frame which can be fixed to the lid of the box
- **Nickel foils** cut to appropriate areas are placed in front of the sample to determine the fluence
Irradiation modes

- **Scanning** irradiation
  - Sample equal or larger in area than the beam
  - User specified scan path to ensure uniform irradiation
  - Typ. samples are scanned in 5mm spaced rows at an horizontal speed of 4mm/s

- **Point-to-point** irradiation
  - Sample smaller than the beam
  - Fixed beam position
  - More sensitive to beam non-uniformity

- **Gafchromic film** is used before irradiation to measure the beam position and profile to set the scan parameters/beam position on sample
Outline

- Overview of the irradiation facility
- Results from sensors irradiations
- Dosimetry
- Ongoing and future irradiation program
- Conclusion
Early results and problems

- For many irradiation runs at the Birmingham cyclotron the \textit{signal} was seen to be anomalously low compared to results at other facilities for the same fluence.
- These irradiation samples also showed evidence of \textit{broad clusters}.
- Prague, Freiburg and Santa Cruz also reported \textit{reduced inter-strip isolation} for sensors irradiated at Birmingham.
- In some cases, \textit{annealing tended to further reduce the signal}.

![Graph showing signal vs bias voltage for ATLAS12 mini sensor before and after irradiation.](image-url)
Investigations - I

- Sensors downstream show results as expected
- They are behind 0.3mm of Si and the Ni foils

ATLAS12 mini sensors
Scanning mode irradiation, $I = 100n\text{A}$, $v = 4\text{mm/s}$

0.5*10^{15}n_{eq}/cm^2
Investigations - II

Sensors downstream (i.e. behind 0.3mm of Al) show good results

Kapton enclosure and Ni foil make no significant difference
Conclusion on investigations

- Signals for sensors with 0.3mm Si/Al upstream during irradiation show good results
- **Contamination in the beam possibly due to some low energy component**
- Consistent with 3-7MeV protons, but other particles are not excluded
- Possible source of these low energy components is at the interaction of the beam with the collimator
- A check of the collimator and a measurement of the Bragg peak close to the collimator are planned to try to get further insight into this
- From an operational point of view this means that we now run with a **0.3mm thick Al-absorber** in front of the samples to be irradiated
Recent results at $1.0 \times 10^{15}$ \text{n}_{eq}/\text{cm}^2

- Six sensors irradiated to $1.0 \times 10^{15}$ \text{n}_{eq}/\text{cm}^2
- Testing more irradiation parameters (current, speed, irradiation mode, ...)
- Four more sensors to test
- Currently upgrading Alibaba setup to reach HV = 1kV

ATLAS12 mini sensors
Red: Point-to-point mode, I = 100nA
Blue: Scanning mode, I = 400nA, v = 4mm/s
Comparison with other facilities

Plot from A. Affolder

Bias voltage = 500V

* Collected Charge (keV)*

* Fluence ($10^{14} n_{eq} \text{ cm}^{-2}$)
Outline

- Overview of the irradiation facility
- Results from sensors irradiations
- Dosimetry
- Ongoing and future irradiation program
- Conclusion
- Geant4 simulation used to determine beam energy at different locations between collimator and sample
- Proton beam energy = 27MeV $\rightarrow$ proton energy at the sample = 23MeV
The fluence is measured using **nickel foils** placed in front of the sample.

The activity of the Ni-57 isotope is measured with a germanium spectrometer.

Intensity of 1377keV peak + cross section for production of Ni-57 = number of incident protons.

Measured and target fluence agree within 10%.
The hardness factor we use for our protons is **2.2**

- However, different values can be found in the literature for 23MeV protons
  - KIT: \( k = 2 \)
  - Tables on RD50: \( k \approx 2.58 \)

We plan to determine \( k \) experimentally with measurement of diode leakage current vs. fluence

*M. Moll, Radiation Damage in Silicon Particle detectors, PhD thesis*
TID relevant for electronics irradiation

\[ \text{d}E/\text{dx} \text{ for } 23\text{Mev protons} = \sim 18 \text{ MeV cm}^2/\text{gr} \]

\[ 1 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2 \rightarrow \sim 130 \text{Mrad} \]

For comparison at the PS the TID for the same fluence is a factor \( \sim 3 \) lower

ABC130 current vs. TID

ATLAS preliminary
Outline

- Overview of the irradiation facility
- Results from sensors irradiations
- Dosimetry
- Ongoing and future irradiation program
- Conclusion
Ongoing and future irradiation program

- Recent irradiations
  - Heavily involved in TID irradiations of **ITk strips ASICs**
  - **LFoundry planar sensor** irradiated to $1 \times 10^{15} n_{eq}/cm^2$ (Uni Bonn)
  - **Scientifica Foam samples** irradiated to $1 \times 10^{15} n_{eq}/cm^2$ (IFIC Valencia)

- Requests
  - Strip barrel mini irradiations (ATLAS ITk collaboration)
  - **ATLAS pixel** quad modules & single AC coupled devices (Liverpool)
  - **Carbon fiber** structures (Liverpool)
  - HV-MUX **JFET** (BNL)
  - Pixel SC active edge module (MPI)
  - **Humidity probes** (Uni Wuppertal)
  - ...

The Birmingham Irradiation Facility
Outline

- Overview of the irradiation facility
- Results from sensors irradiations
- Dosimetry
- Ongoing and future irradiation program
- Conclusion
Conclusion

- The Birmingham irradiation facility is operational with results in good agreement with other facilities

- More work is planned to understand the low energy component responsible for previous contradicting results, and to refine the dosimetry

- A number of irradiations are ongoing and planned within the AIDA-2020 framework, including sensors, ASICs, mechanical components, ...
Acknowledgments

- Many thanks to the team at the MC40 accelerator:
  - Prof. D. Parker
  - Mr. Mike Smith
  - Mr. Robert Goodwin
  - Mr. Robert Wheeler
  - Mr. Gregory Wood
References

- **Talks**
  - “CCE and Signal Broadening with MC40 Irradiations” - James Broughton, [https://indico.cern.ch/event/369608/](https://indico.cern.ch/event/369608/)
  - “Update of irradiation at Birmingham cyclotron” – Daniel Briglin, [https://indico.cern.ch/event/461382/contributions/1132821/attachments/1228086/1799170/ITKFeb16_Birmingham_Irrad_Update.pdf](https://indico.cern.ch/event/461382/contributions/1132821/attachments/1228086/1799170/ITKFeb16_Birmingham_Irrad_Update.pdf)

- **Papers**

- **Weblinks**
  - [http://www.np.ph.bham.ac.uk/pic/cyclotron](http://www.np.ph.bham.ac.uk/pic/cyclotron)
  - [http://aida2020.web.cern.ch/content/uob](http://aida2020.web.cern.ch/content/uob)
The overheating takes the form of brief but large temperature increases during the period that the sensor is moving through the beam spot. This is due to the 27 MeV protons depositing energy in the sensors at a rate of 1.1 W, causing significant temperature increases. Similarly, I-V measurements were made which also show evidence of annealing of the Birmingham sensors. The current of the irradiated Birmingham sensors is significantly larger than the KEK and Los Alamos sensors both before and after annealing.

4. Upgrades

In order to prevent overheating in subsequent irradiations, the maximum beam current was reduced to 0.5 μA. Whilst a temporary solution, this limits the potential to irradiate to high fluences as the scan time is doubled compared to using a beam current of 1 μA. As a more practical solution, improvements were made to the cooling system in order to optimise the air circulation within the cold box.

Cooling system. A Norhof [10] liquid nitrogen (LN$_2$) system using evaporative cooling was installed, as shown in the bottom left of Fig. 6. The LN$_2$ is dripped on to a heat sink located at the base of the cold box. The LN$_2$ evaporates to produce very cold N$_2$ gas. The flow of LN$_2$ into the cold box is adjusted automatically by the Norhof system, which operates by monitoring the temperature and pumping in LN$_2$ to achieve the preset required temperature of Fig. 4.

Charge collection measurement comparing sensors irradiated to $10^{15} n_{eq}/cm^2$ at Birmingham, Los Alamos and KEK. Note: the unusual behaviour of the Birmingham sensor compared to the other facilities. Fig. 5.

Charge collection measurement comparing sensors irradiated to $10^{15} n_{eq}/cm^2$ at Birmingham, Los Alamos and KEK, after Los Alamos and KEK sensors had been annealed by heating to 80°C for 60 min where the behaviour of the sensors is similar among all facilities. Fig. 6.

Fig. 6. The upgraded system installed in the Birmingham Irradiation Facility with the LN$_2$ system and dewar to the left of the scanning system with the new cold box and the Faraday cup with a green stand. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

Fig. 7. Carbon fibre frame for mini sensors (1 cm$^2$) with square recesses to slot in sensors which can be secured using minimal kapton tape and attached to the box lid using the locator holes at the top of the frame where the middle hole is clipped to the box using a spring release.

P. Dervan et al. / Nuclear Instruments and Methods in Physics Research A 796 (2015) 80–84
Cooling

- A Norhof liquid nitrogen (LN2) system using evaporative cooling is installed. The LN2 is dripped on to a heat sink located at the base of the cold box. The LN2 evaporates to produce very cold N2 gas. The flow of LN2 into the cold box is adjusted automatically by the Norhof system, which operates by monitoring the temperature and pumping in LN2 to achieve the preset required temperature of the cold box. The new cooling system can achieve a stable temperature of 50°C in 30 minutes.
Cold box details

- Styrofoam box structure clad with Aluminum foil and Formica
- Thin double skinned Polyamide window to allow beam entry and exit
- Inlets for cooling and N2
- Fans within the box are used to ensure good air circulation
Example of T and RH monitoring during irradiation

- Temperature and humidity logged with Arduino-Uno system. Three temperature and two humidity sensors placed at different locations in the box.

Stable irradiation temperature achieved within 20 minutes.
Temperature on sensor during irradiation
Absorber
@ Ni foil = 24.27MeV
@ sensor = 23.0MeV

No absorber
@ Ni foil = 25.81MeV
@ sensor = 24.60MeV
Beam profile

Absorber

No absorber
Low energy component

- A 3 MeV proton has a range of 107mm +/- 4.5mm in air with a density of 0.00163 g/cm³ (ICRU-104 material)
- Protons must have energy more than this to traverse 10cm of air between collimator and sample
- A 7MeV proton loses around 1MeV in 10cm of air
- A 6.5 MeV proton has a range of 296μm +/- 12.6μm in pure Al so would be stopped
- Values taken from SRIM
Bragg peak

- Optimal energy is 26.85 MeV with a Gaussian spread of 0.15 MeV
- Apparatus placed 1m downstream (only available position at present). Energy loss corrected for this distance
- As a consequence of the large separation between the end of the beam line and apparatus the low energy protons are absorbed in the intervening air. So there is no low energy components shown in the plot
- Will redo measurements closer to the collimator when possible - should then see low energy components
- This is important to check if some of the low energy protons may have energies greater than 6.5MeV and so not be stopped by the 0.3mmm of Al. We need to check that our 0.3mm of Al is sufficient to remove the low energy contamination

![Graph showing dose vs depth in Perspex](image.png)
Various beams and measurement sites: we get reasonable curves

ATLAS12A proton irradiations

X10^{15} 1-\text{MeV} \text{n/cm}^2

after 80\text{min}@60^\circ\text{C} annealing

K. Hara, HSTD10, Xi'an China, 25-29 Sep 2015
ATLAS12A proton irradiations

Various beams and measurement sites: we get reasonable curves after 80 min @ 60°C annealing.

K. Hara, HSTD10, Xi'an China, 25-29 Sep 2015