The Birmingham MC40 Cyclotron Facility

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Introduction

The Scanditronix MC40 cyclotron at the University of Birmingham is the latest in a series of particle accelerators operated at Birmingham. Installed in 2004, the cyclotron delivers a flexible range of ions and energies and is used for a wide variety of research and applications. This article briefly details previous particle accelerators at the University before outlining several projects undertaken with the MC40 as an illustration of its capabilities and the breadth of work undertaken.

The history of accelerators at Birmingham

The University of Birmingham has a long history of particle accelerators. In 1938 Marcus Oliphant, Professor of Physics at Birmingham, obtained from Ernest Lawrence a complete set of drawings for the Berkeley 60" cyclotron, and Lord Nuffield provided funds to build a modified copy at Birmingham. Construction was interrupted by WW2, and the Nuffield Cyclotron (Fig. 1) finally entered operation in 1948. It was a fixed frequency (10.5 MHz) machine delivering beams of 10 MeV protons, 20 MeV deuterons, 30 MeV ^{3}He and 40 MeV ^{4}He. Beams of beryllium, carbon, nitrogen, oxygen and neon were also demonstrated. The Nuffield Cyclotron was intensively used, initially for nuclear physics studies and subsequently for radionuclide production (mainly using internal targets). For example, ^{22}Na and ^{109}Cd were supplied to Amersham International. Starting in the 1980s a collaboration with Dudley Road Hospital, Birmingham produced ^{81m}Kr generators for pulmonary ventilation imaging; the parent nuclide, ^{81}Rb, was made by bombarding solid targets of sodium bromide with 40 MeV alpha particles.

Figure 1: The Nuffield Cyclotron.

A symposium in 1998 celebrated 50 years of beams from the Nuffield Cyclotron, at which point it was believed to be the oldest working cyclotron in the world, and was still operating reliably. However, concerns over how to bring the shielding up to the latest standards led to a decision to close it in 1999.

Soon after starting construction of the Nuffield Cyclotron, Oliphant had conceived the idea of a proton synchrotron, and in 1946 it was decided to construct a 1 GeV synchrotron at Birmingham. In 1953 the Birmingham synchrotron became the first proton synchrotron to operate at its full design energy, but by then the Brookhaven Cosmotron was already operating at higher energy and intensity. A programme of research into nucleon-nucleon interactions continued for ten years before the research was transferred to the Rutherford Laboratory, and the synchrotron closed in 1967.

The University's Radial Ridge Cyclotron (Fig. 2) was constructed using the magnet from the 37" cyclotron originally built in Cambridge in the 1930s. This was transferred to Birmingham in 1958 and completely rebuilt as an Azimuthally Varying Field (AVF) cyclotron. Internal beams were first achieved in 1961, and extracted beams from 1963. The Radial Ridge Cyclotron operated at two frequencies: 12 MHz to accelerate 12 MeV deuterons or 24 MeV alphas, and 16 MHz for 33 MeV ^3He. It was the first cyclotron to use axial injection, enabling the use of polarised ion sources, and for a time was the only cyclotron in the world that could deliver polarised beams of both deuterons and ^3He. Until 1986 it was used for nuclear physics research, and thereafter to generate short-lived positron emitting isotopes. As Proton Emission Tomography (PET) was being developed elsewhere as a medical imaging modality, Birmingham pursued the use of PET to study flows in engineering, initially in collaboration with Rolls Royce and Castrol. Mapping the tracer concentration in PET requires acquisition of a large volume of data, and since engineering flows are often much faster compared to metabolic processes in biology, Birmingham adopted the alternative approach of tracking a small positron-emitting particle [1]. This Positron Emission Particle Tracking (PEPT) technique proved extremely powerful for characterising granular and fluid flow in a wide range of engineering situations. The tracer ^{18}F was produced from natural oxygen using the 33 MeV ^3He beam from the Radial Ridge: $^{16}O(^3He,p)^{18}F$. In this way large sand grains (SiO_2) could be directly activated, while smaller particles were indirectly labelled using $^{18}F^-$ ions produced by bombarding natural water. PEPT at Birmingham has grown and alongside the industrial imaging applications, much recent research has focused on understanding granular materials [2-3].

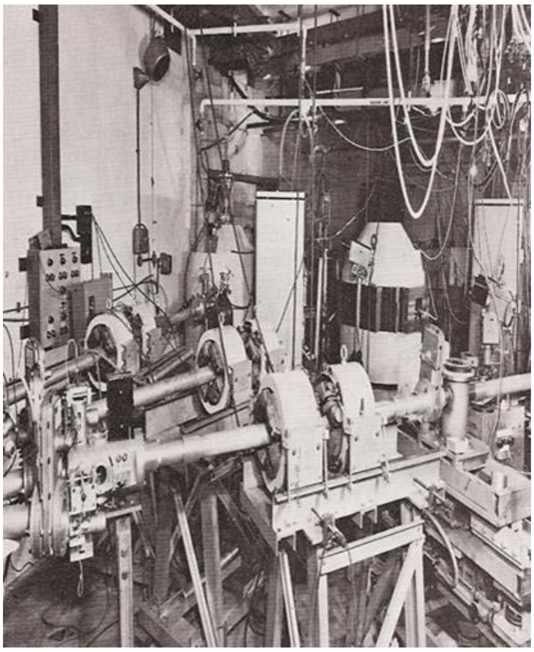


Figure 1: Radial Ridge Cyclotron beamlines.

Completing the list of Birmingham accelerators, the 3 MV Dynamitron was purchased from Radiation Dynamics in the late 1960s and has been operational since 1972. Originally used for a wide range of studies including neutron physics and materials analysis (RBS, ERDA and NRA), for the last two decades the Dynamitron has been dedicated to production of epithermal neutrons for boron neutron capture therapy (BNCT) trials: neutrons from the $^7Li(p,n)^7Be$ reaction – generated by bombarding a lithium metal target with up to 1 mA of 2.8 MeV protons – are then moderated to the desired spectrum.

The MC40 cyclotron

By the late 1990s, the Radial Ridge Cyclotron was becoming increasingly unreliable, so that if the PEPT work was to continue Birmingham needed a replacement cyclotron, and ideally one capable of accelerating ^3He so as to generate ^{18}F from natural oxygen. This implied a positive ion cyclotron though in that period no manufacturer was selling such cyclotrons. In early 2001 it was learnt that the last Scanditronix MC40 delivered, which had been operating at the Veterans Affairs Medical Centre (VAMC), Minneapolis, USA since 1993, would shortly be shut down and offered for sale. Further enquiries confirmed that this machine had been relatively little used and was in good condition. Accordingly a proposal was put to EPSRC and on 29th August 2001 funding of £550k was awarded to cover the purchase of this cyclotron and its transfer to Birmingham.

The Minneapolis cyclotron was shut down in September 2001. After some delays, in November it was offered for sale through a sealed-bid auction organised by GSA, with a closing date of 10th Jan 2002. The University of Birmingham submitted a bid for $551k, and on 29th Jan 2002 it was announced that this bid had been successful.

The timeliness of this was confirmed when in December 2002 the Radial Ridge suffered a major breakdown to the high voltage transformer supplying the RF oscillator. It took three months to work around this problem and get the cyclotron operating again, whereupon just a month later it developed further serious RF problems. Considerable effort was put into trying to repair it but eventually the decision was made to abandon it and concentrate staff effort on commissioning the MC40.

Installation in the redundant "Low Scatter Cell" adjoining the Dynamitron and initial commissioning took almost a year, and first beam was obtained on 4th February 2004, two days before the official opening ceremony (Fig. 3). Commissioning of various beams continued through 2004; the cyclotron started to fulfil its original brief of producing ^{18}F for PEPT, and other applications were sought.

Figure 3: The MC40 Cyclotron, photographed during the opening ceremony in Birmingham: the upper yoke is raised to show the internals.

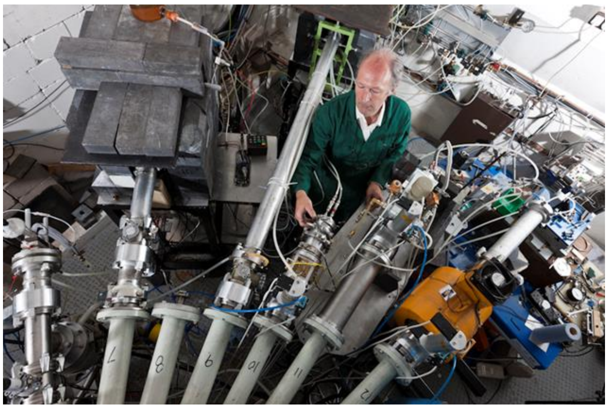


Figure 4: Beamlines emerging from the 12-way switching magnet: the lead enclosure houses one of the ^{81}Rb production targets.

In recommissioning the MC40, advice was sought from the group at Hammersmith Hospital where a similar MC40 had been operating since 1987. In early 2005 it was learnt that the Hammersmith MC40 would be closed in 2006, and it was proposed that Birmingham should take over production of ^{81}Rb for manufacture of ^{81m}Kr generators. Production of ^{81}Rb would thus return to its original home, having transferred to Hammersmith when the Nuffield Cyclotron closed.

In order to manufacture ^{81}Rb regularly as well as maintaining existing programmes, a larger switching magnet was needed, serving more target stations. A 12-way switching magnet was purchased second-hand from Strasbourg where it had previously served the Vivitron accelerator. Installation of this switching magnet required a major shutdown of the MC40, including temporary removal of one RF system. The cyclotron shut down towards the end of 2005 and restarted in February 2006.

Rubidium-81 production started in March 2006 and has continued ever since. By the end of 2017, production had been attempted on over 2900 days. Using a score of 1 for a successful run, 0.5 for a run where some ^{81}Rb was produced but less than required, and 0 for a complete failure, the overall success rate for these 2900 runs is over 96%.

The MC40 facility

During 2006 a beam line was extended out of the cyclotron vault into the adjoining target room. This line was used for nuclear physics studies and also for studying radiation effects, but conflicts soon developed between the nuclear physicists' need for a low-background environment and the demands of the radiation damage community for higher beam currents. Finally, in 2012, the target room was subdivided by a new central shielding wall, and a second beam line was run into the newly-created shielded area. This new beam line is used for high-current radiation damage runs: it has two branches, one used for low-temperature irradiation of silicon devices by colleagues from ATLAS (see later) and the other for metallurgical damage studies of high temperature samples. The original beam line is used for nuclear physics and also (upstream) for general low dose irradiations. This is also where the PRAVDA systems were tested (see later). With completion of this beam line the facility achieved its current layout, as shown in Figure 5.

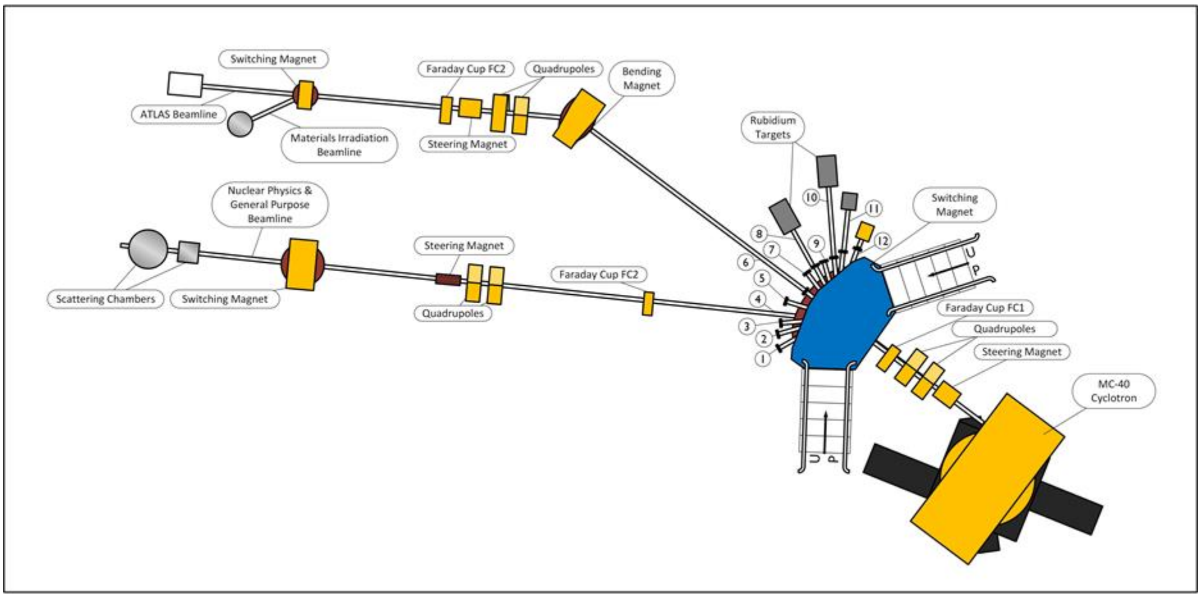


Figure 5: Current layout of the MC40 facility.

The MC40's RF systems can be tuned over the range 27.4 to 14.2 MHz (the original design could go lower, but the resonators were shortened to fit in the low vault at Minneapolis). This gives the nominal operating ranges summarised in Table 1. The N=1 and 2 modes refer to the fundamental frequency and first harmonic respectively, of the radio frequency accelerating voltage.

Beam ion	Energy (N=1)	Energy (N=2)
Protons (^{1}H)	10.8-40 MeV	2.7-10 MeV
Deuterons (^{2}H)	---	5.4 - 20
Helium-3 (^{3}He)	33-50 MeV	8-28 MeV
Helium-4 (^{4}He)	---	10.8 - 40 MeV

Table 1: Commonly produced ions and energies available at the MC40 cyclotron.

In practice the maximum achievable proton energy is around 38 MeV. Helium-3 is run using the recirculating gas system acquired from the decommissioned Hammersmith cyclotron; the MC40 vacuum is maintained using a single diffusion pump whose exhaust is passed through a cold zeolite filter and then returned to the ion source. Additionally, small beams of 46 MeV $^{14}N^{4+}$ and 71 MeV $^{14}N^{5+}$ have also been extracted and used for nuclear physics studies.

Nuclear structure studies

The low-energy nuclear physics group at Birmingham (Tz. Kokalova, M. Freer and C. Wheldon) have developed two scattering chamber set-ups on beamline 4 at the cyclotron. Typically, the larger ~0.5 m diameter cylindrical scattering chamber shown on Figure 5 is used for particle spectroscopy studies, focusing on light nuclei. In particular, the group specialises in break-up reactions [4] to explore cluster states – nuclear states in which the protons and neutrons exhibit sub-structure within the atomic nucleus, such as the formation of alpha particles. These states play an important role in the formation of the elements [5]. By exciting nuclei above the particle-decay threshold and recording the position and energy of the break-up particles resulting from the decay, the original state can be reconstructed via energy and momentum considerations. Much of this charged-particle spectroscopy work makes use of double-sided silicon strip detectors – position sensitive detectors with orthogonal strips on the front and rear surfaces. By correlating front and back energies the 'pixel' corresponding to a particle hit can be isolated. These detectors also cope well with multiple simultaneous hits providing the energies of the particles are sufficiently different. How states decay is a sensitive probe of their underlying nuclear configuration, thus opening a window on their structure. A recent highlight is the study of the Hoyle state in ^{12}C – the second excited state lying at an excitation energy of 7.654 MeV enhances the reaction rate for ^{12}C synthesis via the triple-alpha or helium-burning process. This enables a third alpha particle to fuse with a 2-alpha-particle ^{8}Be resonance, thus, overcoming the nucleosynthesis bottlenecks that exist due to the absence of stable mass-5 and mass-8 nuclei. As such, the Hoyle excitation in ^{12}C is the key gateway state for heavy element production. Given its importance, the structure of this state is a crucial testing ground for understanding the nuclear force. Although it is known that the Hoyle state has a structure resembling three alpha particles, the precise configuration has hitherto remained elusive despite a myriad of experiments. One novel way of exposing its underlying structure is to measure the branching ratio for decay *directly* into three alpha particles, rather than via the dominant sequential decay mode to ^{8}Be. The previous limit on the direct 3-particle branch was <0.2% [5]. By utilising a carefully planned geometry to remove the dominant background component, a new upper limit of <0.047% for direct disintegration into 3 alpha particles was obtained [6] at the MC40 facility – a factor of five improvement over the previous result. This level of precision lays down a challenge for theorists to calculate branching ratios for various possible structures of this special state. Previously, the first observation of equilateral triangle symmetry in nuclei was made, also in ^{12}C, following the measurement of an excited 5^{-} rotational level at the cyclotron [7], completing a unique rotational fingerprint.

Recently added, the smaller of the two scattering chambers (shown in Fig. 6) enables a compact cube-like configuration of silicon detectors to be mounted around the target. This is optimised for high efficiency particle measurements, but can also be positioned inside a thin-walled aluminium dome to enable particle-gamma coincidence experiments. Around this dome lies a structure for up to 16 lanthanum-bromide gamma-ray detectors as shown in Fig. 6. The current STFC-Birmingham-funded array of ten in-house $LaBr_3$ detectors now enables rotational states built on cluster states to be elucidated as well as timing measurements down to ~50 ps.

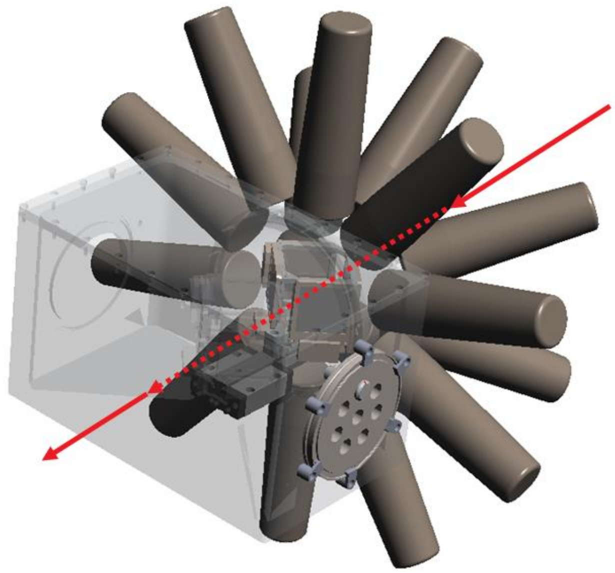


Figure 6: Schematic showing the 'silicon cube' inside the smaller scattering chamber. The tubes indicate the approximate positions of $LaBr_3$ detectors.

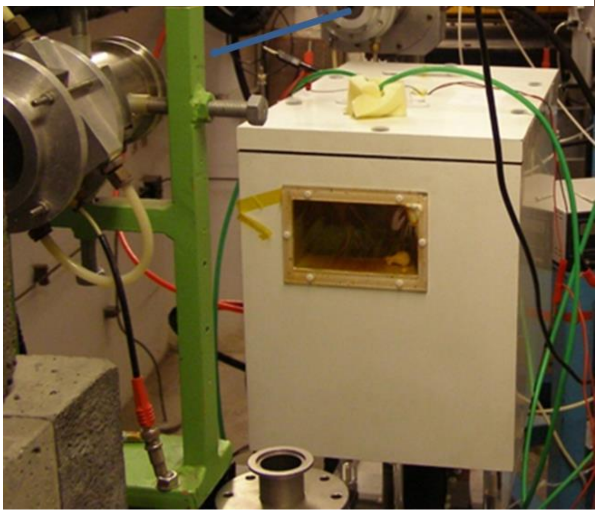
Other physics investigations carried out by the group here include cross-section measurements, using either gamma- or particle spectroscopy as well as resonant scattering using an extended gas target to explore, for example, nuclear molecules – nuclei with clusters bound together by additional covalent neutrons. One such resonant scattering study enabled the observation of previously uncharacterised states in ^{18}F using a ^{4}He gas target and a ^{14}N beam from the cyclotron [8]. The cyclotron is being increasingly exploited for nuclear structure studies and is able to produce internationally competitive results that deepen understanding.

ATLAS irradiations

The high intensity area of the MC40 cyclotron (beam line 6 in Fig. 5) was constructed in 2013 [9] as a joint project by the Universities of Birmingham, Sheffield and Liverpool, to allow high dose-rate radiation damage studies. Initially designed in response to the need for radiation damage trials for the ATLAS detector upgrade at the High Luminosity LHC (HL-LHC) accelerator at CERN, the facility is now part of the European Transnational access programme AIDA-2020, and is being used to irradiate components for the entire HL-LHC upgrade programme.

This beamline can provide up to 2 µA of protons with energies as high as 38 MeV in a beam spot collimated to 10×10 mm^2, giving a flux of up to 10^{13} protons/s/cm^2. As a rule of thumb, at 1 µA the facility can deliver fluences of 10^{15} 1 MeV n_{eq}/cm^2 in 80 s. This is the fluence that silicon strip sensors need to withstand during ten years of operation at the HL- LHC. Typically, a proton energy of 28 MeV and currents of 0.1–0.5 µA are used during irradiations. Dosimetry is determined online using a Faraday Cup and offline by measuring the activity of nickel foils.

Figure 7: HL-LHC irradiations are performed in the controlled environment of the white chamber as it scans through the beam (indicated by the blue arrow).



Irradiations are carried out in a temperature-controlled chamber (Fig. 7) with temperatures as low as –40 °C and humidity well below 10%. The chamber can be scanned through the beam to uniformly irradiate samples with areas larger than the beam spot, and samples can be biased, clocked, and read-out during irradiations.

To-date, hundreds of samples have been irradiated, including silicon sensors, integrated circuits, optical components, and mechanical structures.

PRaVDA

Proton radiotherapy promises clinical advantages over conventional X-ray radiotherapy for certain types of cancers, particularly those in paediatrics and head and neck. The use of charged particles in radiotherapy yields a dose distribution through the patient with a low entrance dose increasing to a maximum (the Bragg peak) beyond which no dose is deposited. Due to the nature of the Bragg peak, it is essential to know the energy loss per unit length of the protons (stopping power) of the tissues that the beams will interact with during treatment to ensure that the dose is delivered correctly. Currently, prior to treatment a patient is imaged using X-ray Computed Tomography (xCT). However, it is not possible to directly extract the stopping powers from an xCT image, instead, the stopping power is inferred from the reconstructed Hounsfield unit, leading to uncertainties on the stopping power, and therefore the proton range, of a few percent.

The low intensity beam area of the MC40 cyclotron has been used intensively over the past five years by the Proton Radiotherapy Verification and Dosimetry Applications (PRaVDA) Consortium [10] for the development of a fully solid state proton Computed Tomography (pCT) instrument. In pCT the proton stopping powers are directly extracted. To acquire a pCT image, it is essential to measure the position, direction, and energy loss of every individual proton. PRaVDA achieve this using large format, radiation hard silicon strip sensors based on developments for the High Luminosity upgrade of the LHC at CERN. The PRaVDA instrument consists of 33 such sensors: four triplets of sensors measure the position and trajectory of the protons; and 21 sensors interleaved with Perspex measure the residual range of the proton after the object being imaged. The MC40 cyclotron was used to test the response to protons of all 33 layers, the radiation hardness of the read out electronics, the tracking performance of the sensor triplets, and the timing synchronisation of the whole instrument. Following successful commissioning with the MC40 cyclotron, a pCT image has been obtained using the clinical proton therapy beamline at iThemba LABS in South Africa. The uncertainty on the stopping powers for all materials imaged is better than 1.6%.

In addition to proton imaging, research is also conducted using the MC40 cyclotron to develop techniques to verify the proton beam before treatment, and monitor the dose delivery during treatment. The facility is a part of the *EPSRC Proton Therapy Network+* which can support access to the MC40 cyclotron for proton therapy research [11][12].

Summary

The MC40 cyclotron has shown itself to be a versatile machine for both research and applications. At the facility, nuclear structure investigations coexist happily with applications such as detector testing, radiation hardness irradiations and routine production of both PEPT and medical isotopes. Over the last five years the activities have broadened significantly. The cyclotron is only half way through its expected life, and, as the UK's only university-based cyclotron laboratory, a future with an expanding research role will complement the long established applications and PEPT research, bringing benefits to more users from across the UK nuclear community.

Acknowledgements

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