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Position sensitive detector applications in nuclear physics and nuclear industry

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Abstract: The Birmingham Cyclotron and associated facilities have an active programme of detector use and irradiation, ranging from nuclear physics and related applications to positron imaging and radiation damage studies. In 2022 a new high flux neutron source (HF-ADNeF) will be installed and commissioned, extending the present charged-particle studies to neutron physics and neutron damage. An overview of the Birmingham Cyclotron Facility is given along with details of the accelerator-driven neutron source. Several examples around detector testing, nuclear physics and positron imaging are outlined.

Keywords: Accelerator Applications; Particle tracking detectors; Neutron sources; Particle identification methods

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1 Overview of the Birmingham Cyclotron Facility

The Birmingham Cyclotron [1, 2] is a Scanditronix MC40 machine capable of routinely accelerating tens of microAmps of hydrogen and helium isotopes. The available beam energies for these light positive-ion species are given in table 1. The arc-discharge source can, in principle, generate positive ions of a wider range of isotopes, however, to-date external beam development has only been carried out for nitrogen isotopes for nuclear physics studies.

Table 1. Beam energies available for light ions for the fundamental and first harmonic frequency modes.

Beam species	Energy range (MeV)	
Isotope	Fundamental	First harmonic
^{1}H (protons)	10.8-40	2.7-10.0
^{2}H (deuterons)	-	5.4-19.8
^{3}He (helium-3)	33.0-50.0	8.0-28.0
^{4}He (alphas)	-	10.8-40.0

The cyclotron is located in a shielded vault and the extracted beam passes to a 12-way dipole switching magnetic. While ten end-stations are located in the vault, two beamlines transport beams to two separate areas of the target room—the high-intensity area and low-intensity general purpose area. The layout of the facility in shown in figure 1.

The cyclotron is used for a wide variety of applications and during evenings operates 50 weeks per year producing krypton-81m generators. The parent isotope is ^{81}Rb, formed in the ^{82}Kr$(p, 2n)^{81}$Rb reaction induced by 26–28 MeV protons. This is supplied to hospitals across the country for lung imaging via SPECT, as ^{81m}Kr ($t_{1/2}$ = 13 s) decays by emitting a 190 keV γ ray. Another daily production is that of tracers for the Positron Imaging Centre (PIC) that performs Positron Emission Particle Tracking (PEPT) [4] for imaging industrial processes.

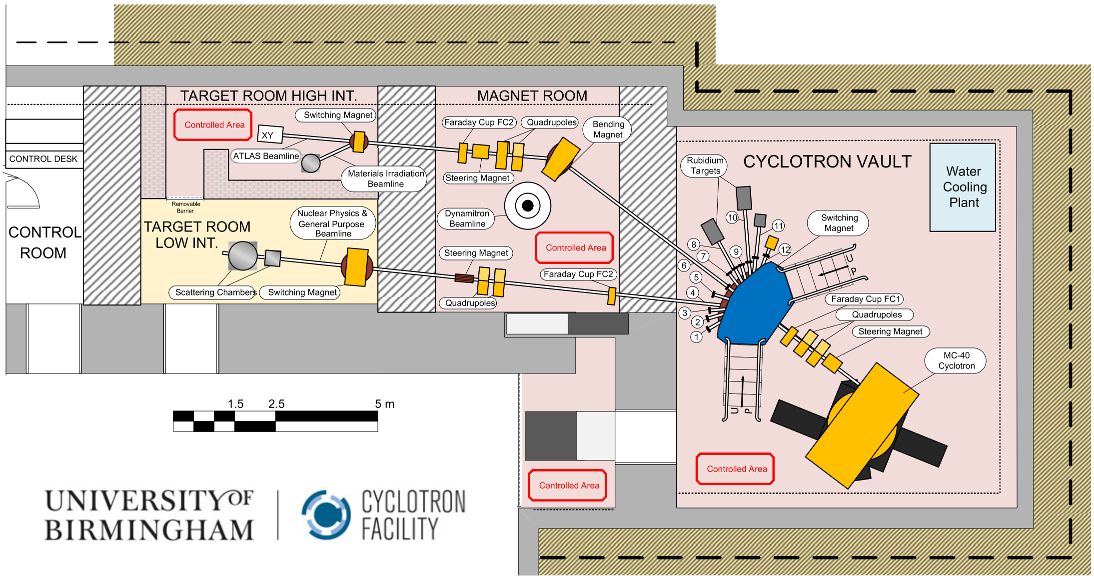

Figure 1. Section of the floor plan showing the layout of the cyclotron facility adapted from ref. [3]. The MC40 and beam-line components (yellow), the switching magnet (blue) and reaction chambers (grey) are indicated. The two beamlines that provide beams to the high- and low-intensity areas of the target room are also shown. The concentric black and white circles in the magnet room indicate the position of neutron target room (see section 5) one floor below the cyclotron level.

Other regular activities at the cyclotron are thin-layer activations for tribology — studies of friction and wear — e.g. for engine components, isotopes for radiation standards, curiosity-driven nuclear physics research and training of the next generation of scientists via hands-on particle spectroscopy courses.

In the following sections, examples related to the detector irradiation work, PEPT imaging (and associated new camera technology) and the nuclear physics apparatus are given.

2 Detector irradiations

Following its initial development by the Universities of Birmingham, Liverpool and Sheffield as part of STFC support for the UK's ATLAS Upgrade contributions, the high-irradiation beamline has been available as a Transnational Access Facility since 2015 via the AIDA (Advanced European Infrastructure for Detectors at Accelerators) initiative. This beamline (beamline 6 in figure 1) can reach the fluence expected at the high-luminosity LHC — $\sim 10^{15}$ 1 MeV n_{eq} cm^{-2} — within a few hours of irradiation. To achieve this, 27 MeV protons at up to 400 nA are steered to a temperature controlled *XY* scanning system (indicated in figure 1). Evaporative cooling using liquid nitrogen means temperatures down to −40°C are possible with humidities as low as 10%. This detector irradiation research is led by BILPA (Birmingham Instrumentation Laboratory for Particle physics and Application) at Birmingham [4]. The AIDA2020 access programme delivered 300 hours of beam time to 12 projects with a total of 41 users from ATLAS, LHCb, EIC and ESS, with diverse

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samples such as glass scintillators, glues, foams and readout ASICs being irradiated alongside the more traditional silicon sensors. There is currently a new EURO-LABS access fund for 2022–2026 with the expectation of providing a similar amount of beam time, but with a higher achievable fluence of $\sim 10^{17}$ 1 MeV n_{eq} cm^{-2} — two orders of magnitude more within a 6 hour irradiation slot. This up-grade will meet the requirements for detector testing for future high-energy physics experiments.

3 Nuclear physics particle-γ coincidence set-up

The detector development research carried out at Birmingham, complements many of the physics measurements undertaken. While for particle physics these take place at CERN, the Nuclear Physics Group has a programme of high-impact measurements that is undertaken at smaller overseas facilities using a peripatetic set-up and a versatile in situ detector and acquisition system on the nuclear physics beamline (beamline 4 in figure 1) at the cyclotron facility. This apparatus comprises two scattering chambers; one larger, general purpose particle spectroscopy vacuum vessel that has yielded several high-impact results, see, for example, ref. [5], and a compact, hemispherical chamber around which the Birmingham lanthanum-bromide γ detectors can be placed, close to the in-vacuum double sided silicon-strip detectors (DSSDs) for charged particles. This particle-γ set-up enables the study of weak nuclear decay channels due to the excellent background suppression afforded by such coincidences. This set-up is shown in figure 2.

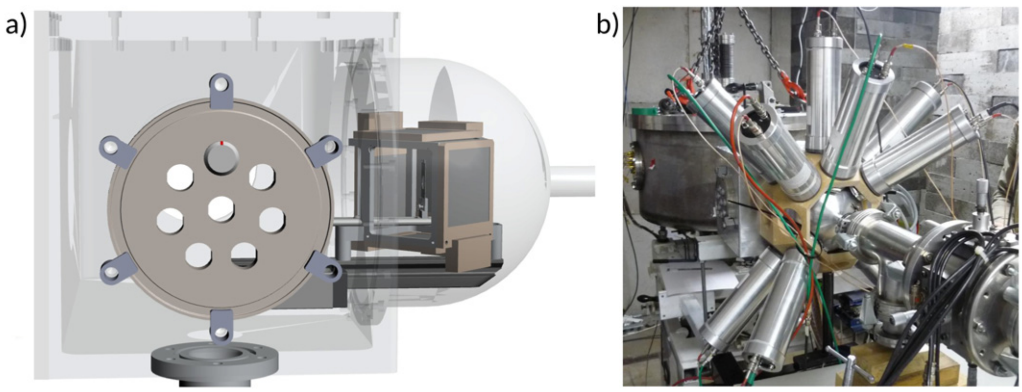

Figure 2. Panel (a) shows the schematic design of the vacuum chamber for the particle-γ investigations. Visible is the internal compact cuboidal silicon detector array. Panel (b) is the view along the beamline of both scattering chambers and the lanthanum-bromide array.

Most recently this capability has been used for nuclear astrophysics studies to gain an insight into elements of nucleosynthesis, in which inelastically scattered α-particles interact with a thick carbon target. The cleanliness of this technique is demonstrated in figure 3 where scattered α-particles from interactions between a 12.2 MeV ^{4}He beam and a thick carbon target were used to isolate the $2^+\gamma$ decaying state in ^{12}C.

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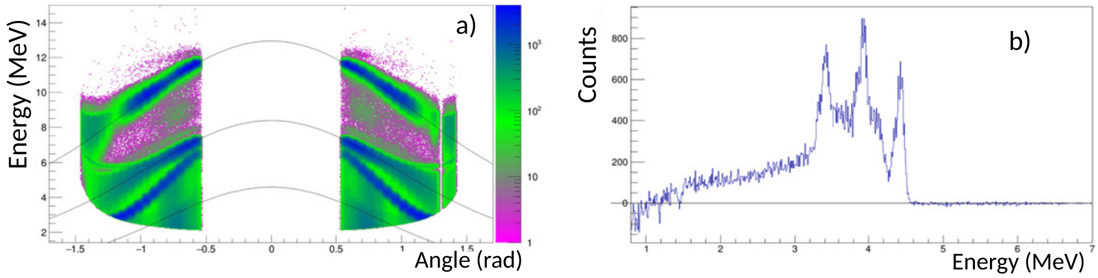

Figure 3. Panel (a) is the 2D histogram of scattering angle versus energy for scattered α particles in the DSSD telescope array using Micron W1 detectors. Three calculated kinematic lines have been overlaid, corresponding to the first three states in ^{12}C and demonstrate the effectiveness of the energy-loss correction. An inverted heat-map-style colour scale is used for intensity. Panel (b) is the coincident γ-ray spectrum gated by the first-excited state locus in panel (a) (indicated by the middle kinematic line). The 4.4 MeV decay and escape peaks are cleanly selected and the large beam-induced background suppressed.

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4 Positron Emission Particle Tracking (PEPT) with SuperPEPT

While precisely locating particles and γ rays is useful for fundamental nuclear physics studies, annihilation radiation following β^+ decay can be used to accurately measure dynamic properties taking place in opaque systems. Whereas in medical PET back-to-back 511 keV annihilation photons are measured to yield the accumulation locations of medical isotopes in the body, the Birmingham group at the Positron Imaging Centre (PIC) has pioneered the PEPT technique [6], which enables tracking of a small number of radioactive tracer particles in real-time. Time-stamped back-to-back 511 keV photons are measured on either side of the system to be investigated by detectors placed at known relative positions, with each pair of photons defining a line of response (LOR). By carefully tuning the activity on the tracer particle used, sufficient LORs can be acquired per desired time-step (e.g. 300 LORs per 0.18 millisecond [7]) to follow the particle(s) in real-time and in three-dimensions. Common positron-emitting isotopes produced at the MC40 cyclotron for use in the PIC are ^{18}F ($t_{1/2}$ = 110 min.), ^{11}C ($t_{1/2}$ = 120 min.) and ^{15}O ($t_{1/2}$ = 2.04 min.), with the choice of tracer dependent on the properties of the system under study. In order to research velocities, flow etc. high spatial resolution data at high rates are needed. The new 'camera' recently developed at the PIC is the SuperPEPT array shown in figure 4. This device combines a large cylindrical field-of-view with MHz data rates to yield sub-millimetre position resolution and sub-millisecond time steps [7]. The array comprises a large number of 8 × 8-way segmented bismuth-germanate (BGO) detectors repurposed from clinical PET scanners and arranged into three closely packed rings. The mechanical support allows the axis of the measurement volume to be either horizontal or vertical. Such a step change in capabilities compared to previous PEPT cameras opens possibilities for characterising the properties of fast moving sources while simultaneously yielding three-dimensional RMS positions to <1 mm; the latter also enabling smaller systems—including biological systems—to be accurately measured due to the high spatial resolution. Due to the increased sensitivity lower activities, compared to previous camera studies, can be used to achieve the same resolution.

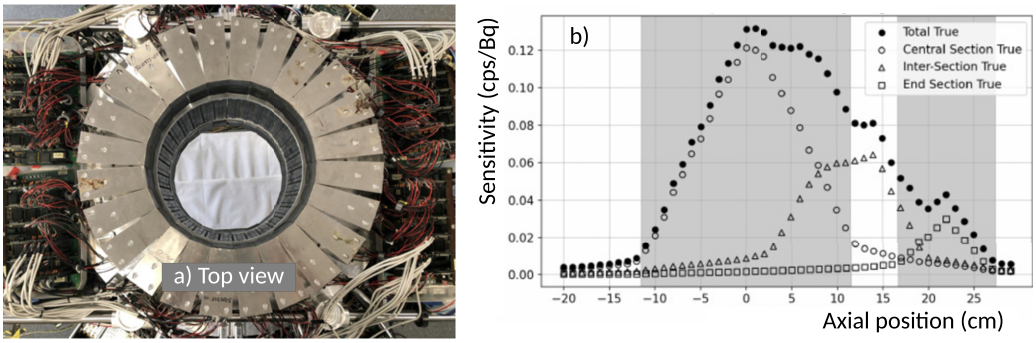

Figure 4. Panel (a) shows SuperPEPT with the axis of the cylindrical measurement volume (inner diameter 40 cm length 54.5 cm) oriented vertically. Panel (b) shows an early measurement of the sensitivity (measured in counts per second per Bq) for an axially aligned source of ^{18}F. The source activity was approximately 20 MBq. The axial extent of the large central ring and the first of the smaller outer ringers are represented by the shaded regions. The second outer ring is under construction.

The MC40 cyclotron underpins all of the above outlined detector systems. The work reported here involves charged-particle beams, but many applications would benefit from neutron fluxes similar to those found in reactors, but with the ability to perform on-line measurements. While the cyclotron can (and does) generate neutrons, these are limited to $< 10^9$ n cm^{-2} s^{-1}, whereas a dedicated, low-energy, high-current proton accelerator can be used to produced reliable neutron fluxes that compete with fluxes available at in the outer channels of research reactors. Such an accelerator-driven neutron source is under construction at Birmingham and described below.

5 Introduction to HF-ADNeF — the high flux accelerator-drive neutron facility

In 2019, University of Birmingham successfully bid for funds to construct a high-flux neutron facility. This £10M project is a national user facility funded by EPSRC and University of Birmingham through the National Nuclear User Facility programme [8] to underpin fission and fusion research for both academic and industry users. The facility (see figure 5) is centred around a high-current proton hyperion-type accelerator supplied by Neutron Therapeutics [9] which delivers protons at currents of >30 mA at energies of 0.4–2.6 MeV. Neutrons at 0.9–0.1 MeV are produced at a cooled, rotating lithium target wheel via the ^{7}Li$(p, n)^7$Be reaction which has an energy threshold of 1.88 MeV. Currently (Dec. 2021), construction of the new bunker to house the accelerator has been completed and the accelerator will be delivered in the first quarter of 2022, with commissioning taking place in Autumn 2022. Fast neutron fluxes of 1×10^{12} n cm^{-2} s^{-1} will be achievable at the target position.

HF-ADNeF is designed to study material damage under neutron irradiation, but the high neutron flux and modular end-stations are applicable to a wide range of studies, beyond nuclear materials research, such as: nuclear fission and fusion data measurements (e.g. neutron capture cross-section data); nuclear waste management research aimed at understanding long term effects of radiation on material characteristics; high-power target development; medical physics including

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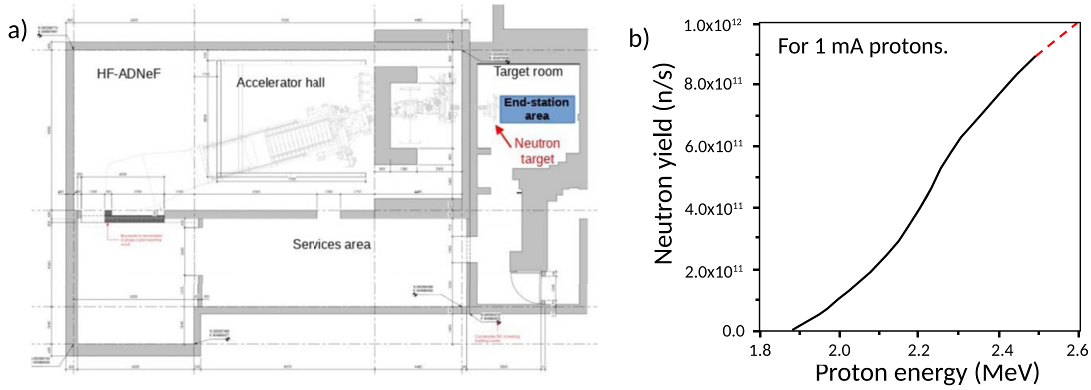

Figure 5. Panel (a) shows the layout of HF-ADNeF including the outline of the accelerator position in the bunker extension and the target room in the Medical Physics building. Panel (b) is adapted from figure 2a of ref. [10] showing neutron yield per milliAmp of proton beam. The plot has been extrapolated (red dashed line) to indicate the expected yield at the HF-ADNeF (maximum) operating energy of 2.6 MeV.

radiobiology on cells and organoids and imaging improvements for novel hadron therapies such as boron neutron capture therapy (BNCT). Other fields that could benefit from neutron beams are industrial and space research on the effects of radiation, nuclear metrology focused on calibrated and controllable neutron sources and nuclear astrophysics research, such as studies of the slow-neutron capture process as the neutron energy spectrum closely resembles that in the relevant stellar environments.

6 Summary

The cyclotron facility enables a large variety of research — both pure and applied — the breadth of which will grow following commissioning of the neutron source. The further development, in 2024, of a dual beam facility, at which materials can be bombarded with, for example, α-beams from the cyclotron while simultaneously undergoing neutron irradiation, will further add to the unique capabilities of the Birmingham accelerators. There is a bright (and busy) future ahead.

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