The Birmingham MC40 Cyclotron

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• Quick History
• Technical description
• Applications
• More on transfer from Minneapolis
History of accelerators at Birmingham

- 60” Nuffield cyclotron (1948-1999) \(10\text{MeV} \, p, \, 40\text{MeV} \, \alpha\)
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- Radial Ridge Cyclotron (1960-2002)  
  (axially injected polarised beams) $12\text{MeV}$ d, $24\text{ MeV}$ $\alpha$, $33\text{MeV}$ $^3\text{He}$
History of accelerators at Birmingham

• 60” Nuffield cyclotron (1948-1999) 10MeV p, 40MeV α

• Radial Ridge Cyclotron (1960-2002) *(axially injected polarised beams)* 12MeV d, 24 MeV α, 33MeV $^3$He

• 1GeV proton synchrotron *(1953-1967)*
  (overtaken during construction by Brookhaven Cosmotron)
History of accelerators at Birmingham

- 60” Nuffield cyclotron (1948-1999) 10MeV p, 40MeV α
- Radial Ridge Cyclotron (1960-2002) (axially injected polarised beams) 12MeV d, 24 MeV α, 33MeV \(^3\)He
- 1GeV Proton synchrotron (1953-1967)
- RDI 3MV Dynamitron (1970 - 3MeV p on Li for BNCT
The MC40 cyclotron

is the third cyclotron to be operated at the University of Birmingham

In 2002-2004 transferred from Minneapolis to Birmingham
In 2005 we added a 12-way switching magnet (blue) [ex Vivitron]
Initially one beam line ran into the adjacent room (past Dynamitron accelerator) and was used for studying radiation effects (e.g. space electronics)
More recently, we were asked to provide high dose-rate damage studies (LHC ATLAS group and metallurgy) so extended a second beam-line into a specially shielded area.
High current irradiation cell: ATLAS line on left, Metallurgy chamber on right

Low current irradiation line: Radiobiology, space applications upstream, Nuclear physics scattering chamber downstream.
Cyclotron equations for particle mass \( m \), charge \( q \) in magnetic field \( B \)
(assuming uniform \( B \), invariant mass)

Velocity \( v \) related to radius \( r \) via \( \frac{mv^2}{r} = qvB \)

(hence constant angular velocity \( \omega = \frac{v}{r} = \frac{qB}{m} \))

At extraction radius \( R \), kinetic energy is

\[
E = \frac{1}{2} mv_R^2 = \frac{1}{2} m \left( \frac{qB}{m} \right)^2 R^2 = \frac{R^2}{2} \frac{q^2}{m} B^2
\]

With \( R=53 \) cm, \( B_{\text{max}} = 1.8 \) T, maximum energies are

- protons \( 40 \) MeV
- deuterons \( 20 \) MeV
- alphas \( 40 \) MeV
- \(^3\text{He}^{2+}\) \( 53 \) MeV
Acceleration is provided by rf voltage on two 90° dees

Accelerating frequency = N x orbital frequency
where N=harmonic number (N=1,2)

In this way we can double the range of orbit frequencies with the same rf system
40 MeV protons, \( N=1 \), requires 26.6 MHz

r

\[
\begin{array}{ccc}
\text{protons} & N=1 & 11-39 \text{ MeV} \\
 & N=2 & 3 - 9.5 \text{ MeV} \\
\text{deuterons} & N=2 & 5.5-19.5 \text{ MeV} \\
\text{\(^4\text{He}^{2+}\)} & N=2 & 11-39 \text{ MeV} \\
\text{\(^3\text{He}^{2+}\)} & N=1 & 33-54 \text{ MeV} \\
 & N=2 & 13-27 \text{ MeV} \\
\end{array}
\]

Also 46 MeV \(^{14}\text{N}^{4+}\) and 70 MeV \(^{14}\text{N}^{5+}\) for nuclear physics
Cyclotron is used for

- Producing positron emitting nuclides for Engineering PET [NOT FDG]
- Producing $^{81}\text{Rb}$ for $^{81}\text{mKr}$ generators
- Thin Layer Activation
- Other isotope production:
  - $^{69}\text{Ge}$ for labelling oil
  - $^{62}\text{Zn}$ supplied to St Thomas’ Hospital London
  - Various irradiations for NPL
- Radiation effects studies:
  - Radiobiology + dosimetry (proton imaging)
  - Space electronics etc
  - ATLAS components
  - Metallurgy of nuclear materials
- Nuclear physics
Positron emission tomography (PET):

Mapping concentration of radioactively-labelled fluid

PET scanner consists of rings of many small detectors, operating in coincidence to detect the pairs of back-to-back $\gamma$-rays from positron annihilation.

After detecting millions of such events a 3D tomographic map of tracer concentration can be reconstructed.
Gamma rays are penetrating – can observe labelled fluid inside process vessels
But PET is slow – requires detection of ~ million coincidence pairs

For fast dynamic information use **Positron emission particle tracking (PEPT):**

Introduce a single labelled particle, and locate it frequently

Currently labelling tracer particles down to 100µm diameter

Can locate tracer particle to within 1mm every 1ms
Positron emission particle tracking (PEPT)
Label a single particle (grain of sand, etc) with positron-emitter (usually $^{18}\text{F}$ from $^{3}\text{He}$ on natural oxygen) and track it as it moves inside equipment.
Original Birmingham Positron Camera

Hawkesworth et al, PSD1  1987

- Originally designed to image lubricant in operating jet engine
- Operational 1984
- Pair of gas filled MWPCs, sensitive area 600x300mm²

- Cathode planes have 50µm lead strips
- Delay line readout
- Each chamber contains a stack of 20 such assemblies
- Total quantum efficiency for 511keV photons 7%

- Spatial resolution 8mm FWHM (+long tails)
Useful count rate limited to around 3000 events/s due to
dead time in readout
random coincidences (resolving time 12.5ns)
“New” Birmingham Positron Camera

*Parker et al, PSD5 1999*

• Installed summer 1999
• Commercially available medical system (ADAC Forte)
• Cost £0.3M
• Pair of gamma camera heads on rotating gantry; separation 250-800mm

Each head contains NaI(Tl) crystal 590x470x16mm³, 55 PMTs each connected to its own ADC; single board computer

<table>
<thead>
<tr>
<th></th>
<th>Old camera</th>
<th>New camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
<td>8mm</td>
<td>4-6mm</td>
</tr>
<tr>
<td>Singles sensitivity</td>
<td>7%</td>
<td>23% total/16% photopeak</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>None</td>
<td>15% FWHM</td>
</tr>
<tr>
<td>Resolving time</td>
<td>12.5ns</td>
<td>7.5ns</td>
</tr>
<tr>
<td>Max true coincidence rate</td>
<td>5kcps</td>
<td>100kcps</td>
</tr>
</tbody>
</table>
Third generation Birmingham systems

developed from redundant medical PET scanners

Leadbeater et al, PSD7-9

Since 2002 PIC has acquired
6 complete PET scanners
and components from two others
(all based on segmented BGO blocks)

These are inherently modular, and can in principle
be reconfigured in different geometries for PEPT.

Can operate at >1Mcps, sensitivity often non-uniform
Twin Screw Extrusion of Polymers
Modular camera installed on Modified Leistritz 27mm TSE

Screw Elements in FOV
On-plant PEPT study : BP, Hull
(240km from Birmingham)

750mm diameter fluidised bed, with central dividing baffle + different air supplies each side of baffle

4 banks of detectors (detector separation 1.2m) give FOV shown
Analysis in terms of movement between four quadrants

Symmetric gas flow
no net circulation

With asymmetric gas flow to promote anticlock circulation
Casting of liquid metal:
PEPT tracking of small alumina inclusion
Examples of tracks obtained with entrained alumina particles of size range 63-100 µm

Examples of the use of PEPT to study filtration of liquid metal using ceramic foam filters. In (a) the alumina particle has become trapped in a 30 ppi filter. In (b) the alumina particle has passed through a 20 ppi filter.
Modular Camera – Metal Casting

Virtual particles after 2 seconds of simulation time

The simulation showed particles rising as they approached the baffle and falling immediately after it. The simulation also showed approximately 2% of particles adhering to the baffle face and the tendency for particles to resist entering the boundary layer.

Particle positions for eight particles from the final experiment
Granular Physics

Especially vibrofluidised granular gases:
- Convection
- Segregation
- Scaling laws
$^{81}\text{Rb}$ (4.6 h)
Parent of $^{81m}\text{Kr}$ (gas), which decays (13s) to g.s. emitting 190 keV gamma

(Parent/daughter generator)

$^{81m}\text{Kr}$ used for imaging lung function using gamma camera
$^{81}\text{Rb production}$

Using the technique developed at MRC Cyclotron Unit (Hammersmith):

- Irradiate target containing $^{82}\text{Kr}$ gas (6 bar pressure) with 29 MeV protons (30µA)
- $^{81}\text{Rb}$ is produced and deposits on walls of target
- At end of irradiation, recover $^{82}\text{Kr}$ gas cryostatically
- Then elute $^{81}\text{Rb}$ from target: 3 x 40ml transferred to dispensing room.
- Finally evacuate target ready for reuse.

Currently making approx 65 generators per week – fairly stable

$^{81}\text{Rb Production statistics}$

Started $^{81}\text{Rb}$ production in March 2006
5 evenings per week, 50 weeks per year

To end of Sept 2014, attempted production on 2116 days,
of which 2045 were successful (97% success rate)

Have produced over 28k generators
Thin Layer Activation

For measuring **wear** on components (especially automotive parts, for R&D): irradiate surface with beam from accelerator to create long-lived radionuclide in well-defined surface layer (typically ~ 50µm deep). Subsequently monitor surface removal by detecting gamma-rays either from remaining layer or from wear debris.

Steel:
- \(^{56}\text{Fe}(p,n)^{56}\text{Co}\) (77 days, 0.85 MeV and 1.24 MeV gammas)
- \(^{56}\text{Fe}(d,n)^{57}\text{Co}\) (270 days, 0.122 MeV gammas)
- Might activate different surfaces with each for simultaneous studies

Aluminium
- Best probably \(^{27}\text{Al}(^{3}\text{He}, 2\alpha)^{22}\text{Na}\) (2.7 years, 0.511 MeV and 1.27 MeV gammas)

Diamond-like carbon (DLC) coatings
- \(^{12}\text{C}(^{3}\text{He}, 2\alpha)^{7}\text{Be}\) (53 days, 0.47 MeV gamma)
PHaVDA

Seeing and Treating Cancer with Protons

- University of Lincoln*
- University of Birmingham*
- University of Liverpool*
- University of Surrey*
- University of Cape Town
- University of Warwick
- University Hospital Birmingham NHS Foundation Trust*
- University Hospital Coventry and Warwickshire NHS Trust*
- National Research Foundation (NRF) - iThemba LABS, SA*
- United Lincolnshire Hospitals NHS Trust
- The Christie NHS Foundation Trust
- ISDI: Image Sensor Design and Innovation Ltd
- aSpect Systems GmbH
- Elekta AB (Publ)
- Advanced Oncotherapy Plc

Funded by wellcome trust
Grant Number 098285

PHaVDA

Local dose curve when protons penetrate the body. The clear increase in effect at the end of the proton path [Bragg Peak] compared with X-rays substantiates the considerable advantages of protons in the treatment of deep tumors.
System Overview

100 – 300 MeV protons

Record incident trajectory

Record exit trajectory

Record residual energy

Repeat many times ....
Operational Modes

**Quality Assurance Mode**
- Beam current = 10 - 100 nA
- 100 - 200 MeV protons

**Treatment Monitoring Mode**
- Beam current = 10 - 100 nA
- 100 - 200 MeV protons

**Patient Imaging Mode**
- Beam current = 0.1 - 1 nA
- 150 - 200 MeV protons
- 0 - 50 MeV protons
Specified and designed complex DAQ
Phys Rev C90 (2014) 024302 \( ^4\text{He}(^{14}\text{N}, \ldots) \) states in \(^{18}\text{F} \) c.n.
Phys Rev C90 (2014) 014319 \( ^{12}\text{C}(^3\text{He},^3\text{He})3\alpha \) states in \(^{12}\text{C} \)
PRL 113 (2014) 012502 \( ^{12}\text{C}(^4\text{He},3\alpha)^4\text{He} \) Triangular state in \(^{12}\text{C} \)
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Lifting : Saturday 8th June 2002
Cyclotron was packed into 56 crates
   - 3 40 foot containers + 2 20 foot containers
Travelled by rail to Montreal and thence by sea to Liverpool where it arrived on 24\textsuperscript{th} July 2002
After clearing customs, arrived in Birmingham 20-23 August

“Active components” were packed in Type A drums and sent air freight

Construction of new supporting floor complete February 2003
Cyclotron has been operational since early 2004

- $p$ $11$-$39$ MeV and $3$-$9$ MeV ($N=2$)
- $d$ $5.5$-$19.5$ MeV
- $\alpha$ $11$-$39$ MeV
- $^3$He $33$-$54$ MeV and $<27$ MeV

Also $46$ MeV $^{14}$N$^{4+}$ and $70$ MeV $^{14}$N$^{5+}$ for nuclear physics