The Christie Proton Beam Therapy Centre and Accelerator Research

Hywel Owen
University of Manchester/Cockcroft Institute
Christie Hospital

• Largest single-site cancer centre in Europe
  – 40,000 patients a year
  – 14,000 new patients

• Dedicated oncology focus

• 16 networked linear accelerators

• Chemotherapy delivery on 15 sites

• Highly specialised surgery for complex and rare cancers

• Regional and national services including
  – Teenage and Young Adult services
  – Pseudomyxoma Peritonei
PBT Centres: Geography

• Established at two leading cancer centres

• Provides UK patients with optimum access to the service, with limited travel times by car or public transport

• Both sites at the centre of regional public transport links

• Ensures as many patients as possible will be able to return home during their treatment
UK Proton Therapy Centres - Update

• Timeline:
  – Pre-qualification questionnaire and technical specification issued
  – Competitive dialogue
  – Manufacturer chosen/ contract placed Q2 2015
    this is when we know what kind of machine it will be
  – First patients 2018

• Specification:
  – 2 centres
  – 230/330 MeV protons only, spot scanning
  – 2 Gy/min/litre
  – 1500 patients (750/centre)
  – 3 or 4 treatment rooms per centre; 3 initially at each

<table>
<thead>
<tr>
<th>Paediatric Indications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Chordoma/Chondrosarcoma</td>
<td>15</td>
</tr>
<tr>
<td>Rhabdomyosarcoma</td>
<td>5</td>
</tr>
<tr>
<td>Orbit</td>
<td>5</td>
</tr>
<tr>
<td>Parameningeal &amp; Head &amp; Neck</td>
<td>15</td>
</tr>
<tr>
<td>Pelvis</td>
<td>10</td>
</tr>
<tr>
<td>Osteosarcoma</td>
<td>3</td>
</tr>
<tr>
<td>Ewings</td>
<td>9</td>
</tr>
<tr>
<td>PPNET (Extra-osseous Ewing's)</td>
<td>5</td>
</tr>
<tr>
<td>Ependymoma</td>
<td>25</td>
</tr>
<tr>
<td>Low Grade Glioma</td>
<td>5</td>
</tr>
<tr>
<td>Optic Pathway Glioma</td>
<td>12</td>
</tr>
<tr>
<td>Craniphayngioma</td>
<td>15</td>
</tr>
<tr>
<td>Medulloblastoma (PNET)</td>
<td>70</td>
</tr>
<tr>
<td>Hodgkins</td>
<td>5</td>
</tr>
<tr>
<td>Retinoblastoma</td>
<td>5</td>
</tr>
<tr>
<td>Meningioma</td>
<td>3</td>
</tr>
<tr>
<td>Intracranial Germinoma</td>
<td>10</td>
</tr>
<tr>
<td>Nasopharynx (Head &amp; Neck)</td>
<td>15</td>
</tr>
<tr>
<td>Difficult Cases (Esthesioneuroblastoma/Neuroblastoma/Liver)</td>
<td>5</td>
</tr>
<tr>
<td>Very Young Age (Extra Cases)</td>
<td>20</td>
</tr>
<tr>
<td><strong>Paediatric TOTAL</strong></td>
<td><strong>252</strong></td>
</tr>
</tbody>
</table>

| Adult Indications                       |                  |
| Choroidal melanoma                      | 100             |
| Ocular / Orbital                        | 25              |
| Chordoma                                | 60              |
| Chondrosarcoma                          | 30              |
| Base of Skull                           |                  |
| Meningioma                              | 100             |
| Acoustic Neuroma                        | 100             |
| Craniophyngioma                         | 10              |
| Craniospinal NOS (Pineal)               | 100             |
| Head & Neck & Paranasal Sinuses         | 300             |
| PNET (medullo/intracranial)             | 30              |
| Difficult Cases                         | 300             |
| **Adult TOTAL**                         | **1235**        |
| **TOTAL**                               | **1487**        |
Advanced Oncotherapy Centre, Harley Street

- Previously tied to BMI Healthcare
- LIGHT linac
  - CERN/TERA 3 GHz SCL
- Presumably no gantry here

Moorgate Private Proton Therapy Centre (2012-ish)

- Private treatment
- CareCapital/Advanced Proton Solutions Holdings Limited
- ProTom Radiance 330 MeV synchrotron
- Gantry interesting
- Single gantry, robotic rotating couch
PBT Centre on Oak Road
- Single accelerator, >230 MeV
- Switching between gantries
- Gantries either 180 or 360 degrees
- Both centres initially have 3 gantries + option for 4th

Centre Layout

Accelerator

Gantries

Single room, e.g. MEVION

Treatment Room
Delivering protons

Multi-room vs single room installations; Depends on cost and size of source

Fast switching can be useful in larger centres

Aitkenhead et al., The British Journal of Radiology, 85 (2012), e1263–e1272
Current Challenges

• Image guidance is a fundamental issue
  – Range uncertainty much more important for protons/carbon than for x-rays
  – Improved imaging – secondary particle imaging
  – Gating, adaptive treatments

• Planning and dose estimation
  – Want dose estimates less susceptible to artefacts; Monte Carlo
  – Want treatment plans robust to patient changes

• Radiobiology
  – Systematic experiments needed to improve data, even for protons
  – Effect of particle type
  – Effect on specific tissue types

• Improved technology
  – More compact carbon accelerators – carbon-11 facility?
  – Higher-energy, economic proton sources
  – Compact gantries, including faster layer switching
  – Fast switching
What do the UK PBT centres want from researchers?

- They don’t want us to provide a facility
  - Commercial provision, vertically-integrated products

- In (rough) order of priority, they want:
  - Advice: are they buying the right facility?
  - Proton treatment planning development
  - Verification of dose (Monte Carlo) and backgrounds (esp. neutrons)
  - Better patient imaging
  - Better diagnostics and dosimetry
  - An upgrade pathway to higher energies (source, gantry)
  - Better understanding of RBE
  - Other particles, C (He?)
  - Compact accelerator sources (e.g. plasma)
The Manchester Method – Range Verification

• 4 connected strands of research, all connected to improved range verification, primarily via proton CT:

• Higher-energy proton sources (see UK PBT specification):
  – ‘NORMA’ 350 MeV proton FFAG (IPAC’14/wepro100)
  – PROBE and IM-PULSE proton boosting projects

• Compact gantries
  – Conventional superconducting gantries
  – Novel FFAG gantries (perhaps SC)

• Proton CT Detectors
  – Collaboration with PRaVDA pCT project (PMB 59,2569 (2014))

• Improved plan validation
  – Development of GEANT4 for fast validation
FFAGs: PAMELA

PAMELA design study successfully completed
- Utilised semi-scaling approach
  - Tune stabilised with higher-order field components
- Next version 330 MeV protons only – proton CT

<table>
<thead>
<tr>
<th>Injection</th>
<th>70 MeV (cyclotron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction</td>
<td>330 MeV</td>
</tr>
<tr>
<td>RF Cycle Rate</td>
<td>1 kHz</td>
</tr>
<tr>
<td>RF Frequency Sweep</td>
<td>10-50 MHz (approx.)</td>
</tr>
<tr>
<td>Acceleration Time</td>
<td>~0.4 ms</td>
</tr>
<tr>
<td>Harmonic Number</td>
<td>~10</td>
</tr>
<tr>
<td>Bunch Structure</td>
<td>Single Bunch</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>0.04 – 1.2 pC</td>
</tr>
<tr>
<td>Charge Stability</td>
<td>~10%</td>
</tr>
<tr>
<td>Average Extracted Current</td>
<td>~0.2 nA</td>
</tr>
<tr>
<td>Average Dose Rate</td>
<td>2 Gy-litre/min</td>
</tr>
<tr>
<td>Extracted Emittance</td>
<td>2 mm x 2 mrad</td>
</tr>
<tr>
<td>Extracted Energy Spread</td>
<td>&lt;0.5%</td>
</tr>
<tr>
<td>Acceleration Voltage</td>
<td>100-200 kV/turn</td>
</tr>
</tbody>
</table>

Courtesy of S. Tygier
NORMA: 30–350 MeV proton scaling FFAG design concept for medical applications

A racetrack with $L_{RT} = 2.0$ m gives around 4.4 m of magnet-free straight for injection and extraction and has a DA of 52.0 mm.mrad.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Circumference [m]</td>
<td>70.1</td>
</tr>
<tr>
<td>Orbit excursion [m]</td>
<td>0.44</td>
</tr>
<tr>
<td>Ring tune (H/V)</td>
<td>7.70 / 2.66</td>
</tr>
<tr>
<td>Horizontal ring tune variation</td>
<td>0.010 (0.13 %)</td>
</tr>
<tr>
<td>Vertical ring tune variation</td>
<td>0.0026 (0.01 %)</td>
</tr>
<tr>
<td>Dynamic aperture [mm.mrad]</td>
<td>52.0</td>
</tr>
</tbody>
</table>

Normal conducting magnets < 1.8 T

DA above 40 mm.mrad at 100 um misalignment.
PROBE – PROton Boosting Extension

- 100 MeV boosting linac
- 250 -> 350 MeV
- Upgrade to existing centres
- Low transmission c.8%, but only pA needed for imaging

- Built on earlier work by TERA on 3 GHz SCL (e.g. AVO)
- 3 GHz linac too long for upgrade
- Working on X-band version
  - c. 70 MV/m possible

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Sc=2.4</th>
<th>Sc=4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3mm Aperture</td>
<td>4mm Aperture</td>
</tr>
<tr>
<td>S-Band (3GHz)</td>
<td>60 MV/m</td>
<td>59 MV/m</td>
</tr>
<tr>
<td>X-Band (12GHz)</td>
<td>67 MV/m</td>
<td>60 MV/m</td>
</tr>
</tbody>
</table>

Sc – modified Poynting vector
TERA TULIP

- TERA concept for linac-based proton therapy
  - Fixed linac
  - Rotating linac - TULIP
- 3 GHz SCL, either with cyclotron or conventional injector
- Structures adopted into AVO LIGHT design
- Also considered for PSI IM-PULSE proposal
PSI Gantry 2

Particle beam from accelerator

Dipoles: bending beam away from/to axis

Coupling point: junction fixed/rotating beamline

Quadrupoles: provide focusing

Scanning magnets

Last bending dipole: bends beam into plane of rotation and iso-center

Nozzle

Iso-center

The Cockcroft Institute of Rutherford Science and Technology
MANCHESTER 1824
The Christie
TOWARDS A FUTURE WITHOUT CANCER
Superconducting Gantries

Test of Toshiba rotating 3.3 T dipole (NIRS gantry)

ProNova Proton Gantry

NIRS/HIMAC Carbon Gantry, 430 MeV/u
NC/SC Gantry Comparison

‘A compact superconducting 330 MeV proton gantry for radiotherapy and computed tomography’

- Uses 3.3T magnets very comparable to NIRS
Monte Carlo Validation of Treatment Plans

- Pencil beam algorithms are deficient in accuracy
- Monte Carlo simulation can improve accuracy, particularly in assessing out-of-field doses
  - Margin reduction of 3mm?
- Many groups working on this, mostly:
  - Simplification of physics (e.g. neglect inelastic)
  - Parallelisation on GPUs
- Our approach: full physics within GEANT4MT
  - Algorithmic improvements to important processes (ionisation slowing)
  - Novel parallelisation: XeonPhi, Cloud
  - Working in GEANT4 collaboration and with PSI

![Normal GEANT4](image1)
![Improved ionisation algorithm](image2)

Identical results, 3x faster

Treatment plan validation using:
- Single Xeon Phi card: 1 hour
- Google Cloud: 5 minutes
Christie Research Beamline

- Utilisation of 4th room
- Funded by Christie charity (£4.8M)
- Around 10.5m straight line space available

- Full clinical beam parameters available:
  - 70-250 MeV
  - 1 Gy/min
  - C. 10 mm-mrad

- Capable of various tests:
  - Accelerator
  - Detectors/imaging
  - Radiobiology

- Design underway
  - Seeking potential user interest
Isotope Provision

• Major focus on impending 99mTc shortage
• Important points:
  – Shortage period 2016 – 2020
  – AECL NRU may irradiate 2016-2018 to alleviate shortage
  – New reactors may replace old by 2020 (ish)
  – Cyclotrons are best accelerator option – this is a solved problem
    • Licensing is the main issue now
  – No simple state-funded way to fund secure supply: rely on market
  – New market entrants considering business case: security?
  – Price point is about 1$/mCi

• UK isotope workshop 26/27 March: https://eventbooking.stfc.ac.uk/news-events/compact-accelerators-for-isotope-production-254