Beam production techniques for hadron therapy

Marco Schippers
Contents

• Facility configuration
• Dose delivery techniques
• Accelerators
• New accelerator developments
Facility configuration

- 1 accelerator
- 3-5 treatment rooms (incl 2-4 gantries)
- Beam to 1 room at the time
Proton therapy facility: modules

PSI
ACCEL/Varian cyclotron

IBA

accelerator
energy selection
beam transport
gantry / fixed hor. line

Tsukuba

Beam delivery techniques for hadron therapy

Marco Schippers, PSI Winterschool, Jan 2010
Proton therapy facility: modules

However, NOT independent.....

Beam delivery => accelerator and energy selection
Dose delivery techniques
Methods:
1) Vary energy in accelerator (synchrotron)
2) Slow down from fixed to desired energy
   - degrade in beam line (PSI)
   - modulate just before patient (in “nozzle”)

Considerations:
how fast?   how accurate?   effect on beam?
Dose delivery techniques: **Width**

**transversal spread:**

- **scattering** (protons only)
- **scanning** (all hadrons)

- Scatter syst.
- Collimator
Proton therapy with a scattered beam

Requirements for accelerator:
- stable beam position
- enough intensity
- enough energy

Energy modulation
Range compensation
Scatter foils
Collimator
Pencil beam scanning

Spot scanning: **step&shoot**

Continuous scanning

kHz-Intensity modulation

Requirements for accelerator:
- stable beam position

allows fast target **repainting:**
15-30 scans / 2 min.

Requirements for accelerator:
- stable beam position
- continuous and stable beam
- fast adjustable beam intensity
- fast adjustable beam energy
Accelerators
Accelerator

Source

250 MeV

250 000 000 Volt
Present accelerator choice

Protons
- In use, $\varnothing 3.5-5$ m
- E.g.: Boston, Florida, Seoul, Wanjie, PSI, München, Orsay

Carbon ions
- In design, $\varnothing 6$ m

Cyclotron

Synchrotron
- In use, $\varnothing 8-10$ m
- E.g.: Loma Linda, Houston, Tsukuba

In use, $\varnothing 25$ m

Beam delivery techniques for hadron therapy
Synchrotron (1945)

Extraction into beam line

Ring:
  - acceleration to desired E
  - storing of the beam

Injection in ring at 7 MeV/nucl

2 linear accelerators in series

Magnet to select ion source

Ion sources for different particles

(DKFZ, GSI, Siemens)
Beam extraction from synchrotron

( Hitachi )

RF-driven extraction
Synchrotron beam structure: noisy & spills

“spill” time
- fill ring with $\sim10^9$ particles
- accelerate to desired energy
- extract slowly during 1-10 sec
- decelerate and dump unused particles

Beam delivery techniques for hadron therapy
Marco Schippers, PSI Winterschool, Jan 2010
Cyclotron (1930)

Ernest Lawrence (1901-1958)

At each electrode border:
Energy gain $\Delta E = V_{\text{dee}}$

RF-Electrodes: 2 “Dees”

Ion source

Extractor: $-HV$

Magnet
Circular orbits:

Centripetal force = Magnetic force

\[ \frac{mv^2}{r} = Bqv \]

\[ T_{\text{circle}} = \frac{2\pi m}{Bq} \]

\[ T_{\text{circle}} \text{ independent from orbit radius } r \]

- \( m \) = mass
- \( v \) = speed
- \( r \) = orbit radius
- \( B \) = magnetic field
- \( q \) = charge
Cyclotron

PSI Injector 1, 72 MeV, 1970

12 MeV cyclotron (UC, 1940)

230 MeV cyclotron (IBA, 1996)

80 keV protons
250 MeV proton cyclotron (ACCEL/Varian)

Closed He system
4 x 1.5 W @4K

Proton source

Superconducting coils
=> 2.4 - 3.8 T

4 RF-cavities
~100 kV on 4 Dees

ACCEL
300 kW
90 tons

1.4 m
3.4 m
Internal proton source

-80 kV

Dee 1

~5 cm

anode
cathode at -HV
anode
cathode at -HV

pole

pole
Max. intensity set by:
Ion source + slits

Deflector plate: sets requested intensity
- within 50 µs
- 5% accuracy

currently only possible with a cyclotron
Extraction from cyclotron

Electrostatic extraction elements

Low radioactivity

(ACCEL / Varian)
Beam-energy adjustment

Degrader unit

Steerer Q Q Q Kicker

All following magnets: 1% field change in 50 ms

Dipole magnets in beam line:
1.1 T
190 A
100 A/s (1-1.4 H)

Carbon wedge degrader
238-70 MeV
5 mm ΔRange in 50 ms
Energy scanning, Estep ~5 mm range in water.
Energy scanning, Estep ~5 mm range in water.
Energy scanning, $E_{step} \sim 5$ mm range in water.
### some differences…

<table>
<thead>
<tr>
<th></th>
<th>cyclotron</th>
<th>synchrotron</th>
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</thead>
<tbody>
<tr>
<td>Carbon ions</td>
<td>in development</td>
<td>easy</td>
</tr>
<tr>
<td>Change particle</td>
<td>in development</td>
<td>easy</td>
</tr>
<tr>
<td>Time structure</td>
<td>continuous</td>
<td>dead time</td>
</tr>
<tr>
<td>Fast E-scanning</td>
<td>degrader</td>
<td>next spill</td>
</tr>
<tr>
<td>Activation degrader</td>
<td>to be shielded</td>
<td>no</td>
</tr>
<tr>
<td>Intensity</td>
<td>“any”, adjustable</td>
<td>limited, per spill</td>
</tr>
<tr>
<td>Intensity stability</td>
<td>3-5%</td>
<td>15-20%</td>
</tr>
<tr>
<td>Size $\varnothing$</td>
<td>3.5 (p)-6 m (C)</td>
<td>6(p)-25 m (C)</td>
</tr>
<tr>
<td>Scattering</td>
<td>ok</td>
<td>ok</td>
</tr>
<tr>
<td>Spot scanning</td>
<td>ok</td>
<td>ok</td>
</tr>
<tr>
<td>Fast continuous scanning</td>
<td>ok</td>
<td>difficult</td>
</tr>
</tbody>
</table>

Beam delivery techniques for hadron therapy
The Holy Grail for proton therapy:

one small (cheap) accelerator per treatment room
New accelerator types....
Small cyclotron on a gantry

Proposal of H. Blosser et al., 1989:
- 250 MeV
- 52 tons, on gantry
- B(0) = 5.5 Tesla

H. Blosser, NSCL (~1990):
cyclotron for neutron therapy;
30 MeV p, mounted on a gantry
Used in Harper Hospital, Detroit

Fig. 9 -- Drawing showing synchrocyclotron rotating gantry arrangement with energy shifting wedge just after the cyclotron. Energy shifting can optionally be accomplished just ahead of the patient.

Fig. 2 Photo of the superconducting medical cyclotron on its gantry. Dr. William Powers and
— No beam extracted yet (oct 2009)
— Many uncertainties on performance and reliability
( @ limit of current technology )
— No beam analysis
— Neutrons ?
Carbon-ion cyclotrons

- Proton (250 MeV) : Range in water = 38 cm, 2.43 Tm
- Helium 2+ (250 MeV/nucl) : Range = 33 cm, 4.86 Tm
- Carbon 6+ (450 MeV/nucl) : Range = 33 cm, 6.83 Tm

⇒ Cyclotron radius of is \( 2.8 \times R \) proton cyclotron
⇒ \( \sim 2.8^2 = 8 \times \) more iron ⇒ 700-800 tons
Accelerator choice

Archade project

IBA

Carbon ions

Protons

700 tons

SC coils

Ø 7 m

Int. Conf. Cyclotron and appl, Tokyo 2004

IBA C400 CYCLOTRON PROJECT FOR HADRON THERAPY

Y. Jongen, M. Abs, W. Beeckman, A. Blondin, W. Kleeven, D. Vandeplassche, S. Zuremba, IBA, Belgium

Start with protons AND

- $\alpha$ + (up to 12.5 cm:) Carbon
- Second step: also 450 MeV/nucl Carbon

PSI design for 2-step approach
**Fixed Field Alternating Gradient accelerator (FFAG)**

**Advantage:**
- Fast energy change in accelerator

**Disadvantages:**
- Heavy (100-200 tons)
- Injector cyclotron needed
- Pulsed

**Recipe:**
1) inject into ring
2) RF until E reached
3) extract.

**Proof of principle FFAG accelerator** at KEK in Japan. (Muri et al)
High gradient (100 MeV/m) Linac (dielectric wall)

- electrode, **pulsed** High Voltage
- Dielectric material
- 2 ns pulses with 100mA protons at 10 Hz

**needed:** 100 MV/m 20 MV/m
**reached:** (2009)

- Pulsed beam
- Low duty cycle
- dose accuracy?

Caporaso et al, Nucl Instr Meth B 261 (2007) 777
New accelerator types

Laser driven proton accelerator

Fig. 1. A schematic diagram showing the treatment head of a laser-proton therapy system.

Fig. 3. A schematic diagram showing the particle selection, beam collimation and focusing process.

C.M. Ma, Laser Physics, 2006, Vol. 16, No. 4, pp. 639
New accelerator types

Cyclotron driven linac

Fig. 3. Artist’s view of LIBO with the cyclotron and a rotating gantry.

Plasma wake field accelerator

(electron) energy doubler


Accelerator choice (protons)

- Cyclotron
- Synchrotron
- Synchrocyclotron
- Cyclotron driven linac
- FFAG
- Dielectr. wall linacs
- Lasers
- Plasma wake field

Current Useability

Quality

Time until useable

Now

Mañana
Summary of accelerator specs

- Time structure: continuous/pulsed
- Intensity (stability)
- Beam position stability
- (fast) E-scanning possible?
- Control; area/mode changes
- Activation of components
- Reliability, service friendliness
- Control system: modularity
- Size, weight, power
Concerns on new accelerators:
1) **at least the same quality** as we have now?
   and, if yes:
2) **advantages** (costs?) and **when available**?

Concerns on future developments:
Industry is now “**producing**” particle therapy.
=> however: **reluctance to invest** in next steps
=> **cheap particles could be disadvantageous**
Pick your choice how to accelerate... 

the choice is up to you!
24 h after beam off, April 2008
(extracted beam integral: 200 μA·h)

- on pole: 400 - 500 μSv/h
- mid plane: 250 - 400 μSv/h

10 cm unshielded degr. 500 - 1000 μSv/h
next to shielded degrader 10 - 20 μSv/h

>80% extraction eff. => Low dose to staff
Relativity in high-E cyclotrons

\[ T_{\text{circle}} = \frac{2\pi m}{Bq} \]

=> \( T_{\text{circle}} \) constant for all radii

However, when \( \nu \to c: \)

\[ m = \frac{m_0}{\sqrt{1 - \nu^2/c^2}} \]

e.g: 250 MeV p: \( \nu/c=0.61 \) => \( m=1.27m_0 \)

=> \( T_{\text{circle}} \) increases with radius => particles lose pace with RF.

Remedy: increase \( B \) with radius
New accelerator types

Gantry with integrated accelerator and ESS

Energy Selection System

synchro-cyclotron

8-10 T field:
250 MeV synchro-cyclotron
⇒ pulsed beam (~1 kHz)
⇒ low duty cycle
FFAG optics for a Gantry

<table>
<thead>
<tr>
<th>Magnet</th>
<th>$L (m)$</th>
<th>$B (T)$</th>
<th>$G (T/m)$</th>
<th>$A_p (m)$</th>
<th>$B_{max} (T)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BD</td>
<td>0.38</td>
<td>3.2-4.1</td>
<td>52.6</td>
<td>±0.008</td>
<td>4.5</td>
</tr>
<tr>
<td>BF</td>
<td>0.40</td>
<td>1.98</td>
<td>54</td>
<td>±0.015</td>
<td>2.8</td>
</tr>
</tbody>
</table>

D.Trbojevic et al., Proc PAC07